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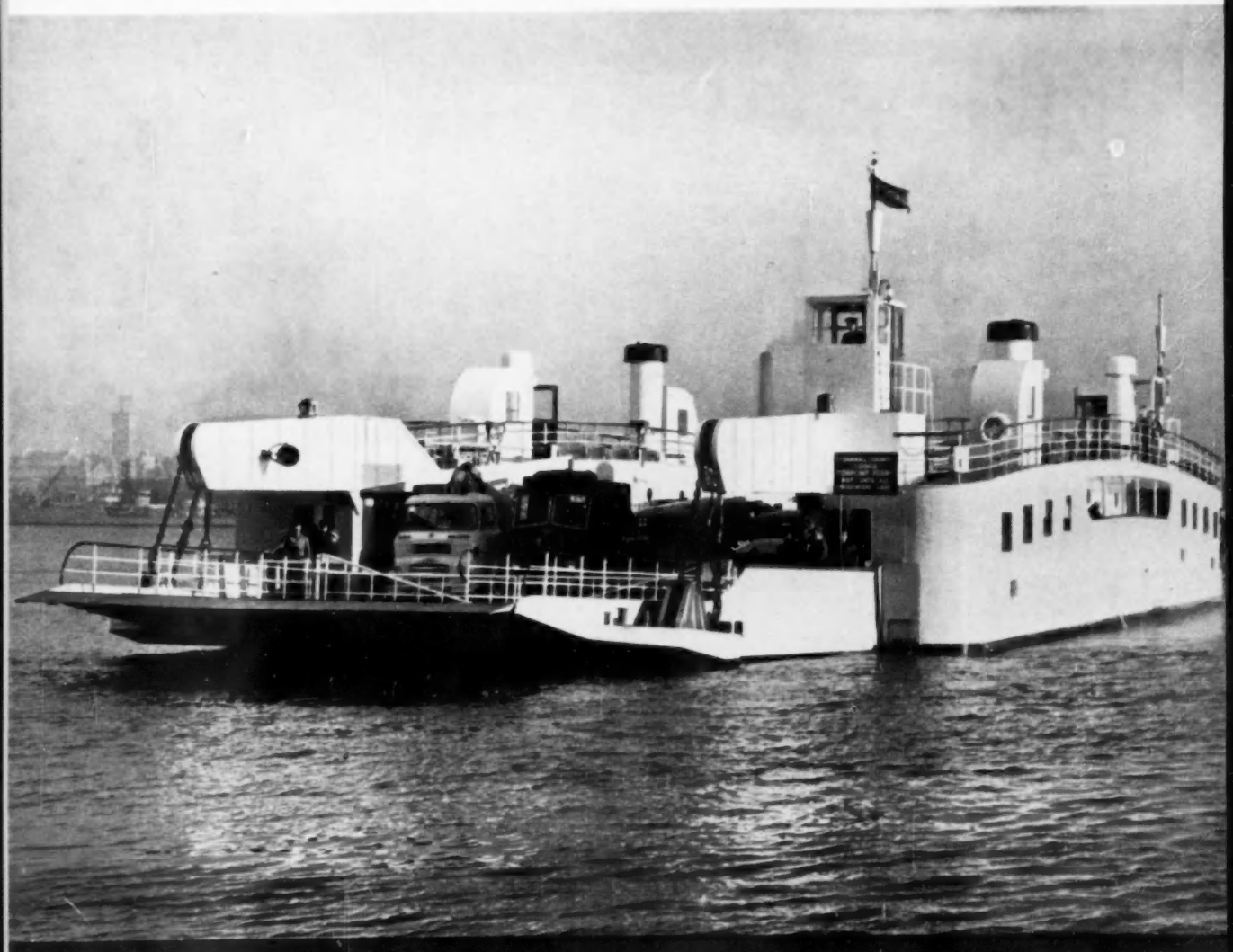

Chain Ferry at Torpoint

THE GENERAL ELECTRIC COMPANY LIMITED OF ENGLAND

Volume 28, number 2

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CONTENTS

Page

50 Frontispiece—Supersonic Wind Tunnel at R.A.E. Bedford

51 Wind Tunnel for High Supersonic Speeds
By J. H. Meacock, A. L. Baxter and E. P. von Bergen

62 First 400 kV Oil-filled Cable in Great Britain

66 Corona Discharge Voltage Stabilizers
By R. O. Jenkins

72 Structural Design and Development of Graphite Reactor Cores
By R. W. Bailey and H. A. Cox

79 Development of Guidance Equipment for the Seaslug Missile
By J. M. C. Pinkham

90 Technical Literature

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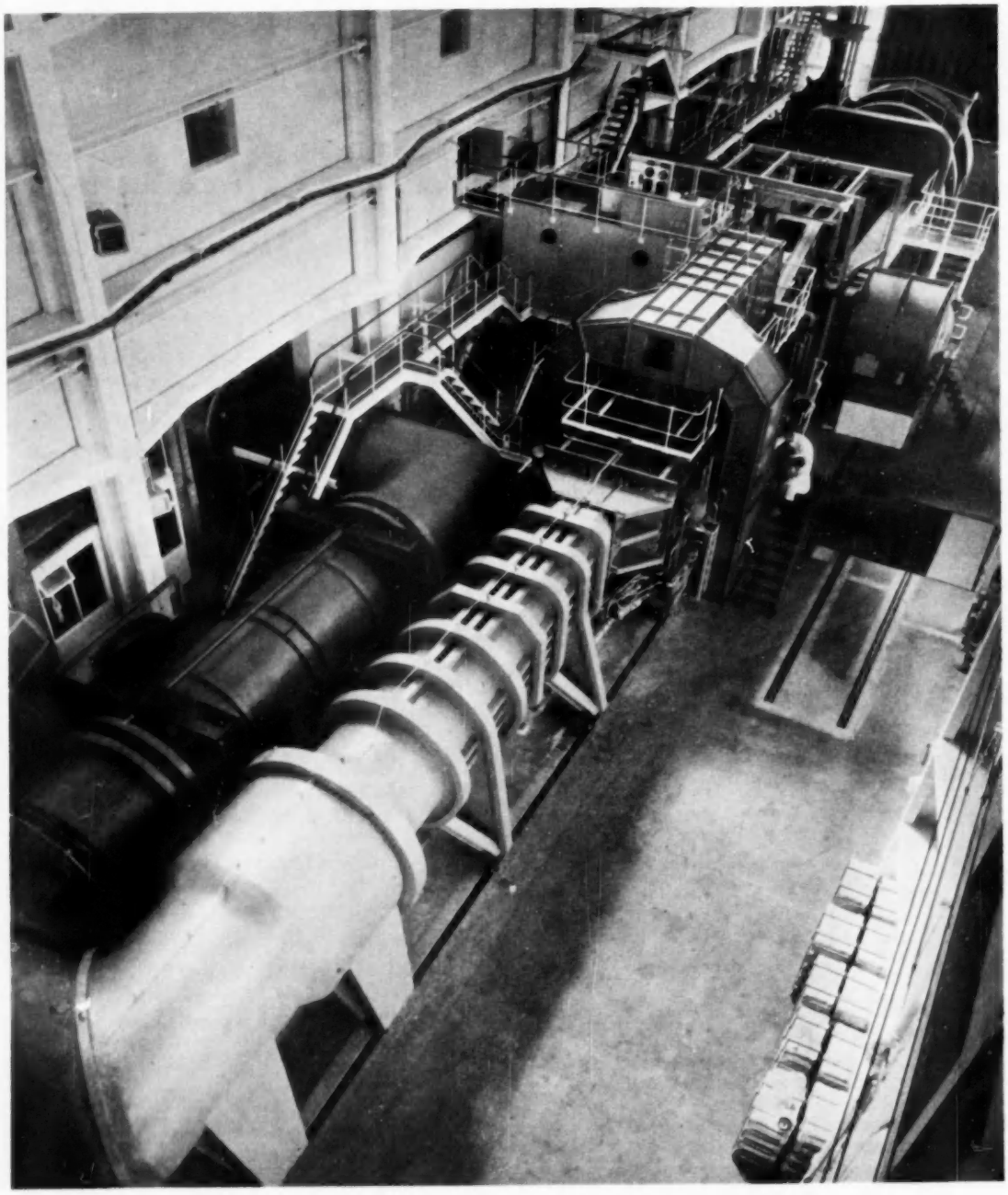
COVER PICTURE

One of the two new diesel-electric chain ferries now in operation between Devonport and Torpoint, on the A38 route to Cornwall.

The 250 h.p. propulsion and control equipments for these vessels were supplied by G.E.C.

Acknowledgement is due to the shipbuilders, John I. Thornycroft & Co. Ltd., for permission to publish this photograph.



Supersonic wind tunnel at the Royal Aircraft Establishment, Bedford.

Wind Tunnel for High Supersonic Speeds

By J. H. MEACOCK, B.Sc., A.M.I.Mech.E., A.M.I.E.E., and A. L. BAXTER, A.M.I.Mech.E., Engineering Group, Erith, and E. P. von BERGEN, M.A., Hirst Research Centre.

AN important addition to British research facilities in the field of high-speed flight was made in March 1961, when a new 4 ft by 3 ft supersonic wind tunnel was opened at the Royal Aircraft Establishment, Bedford, by the Rt. Hon. Peter Thorneycroft, M.P., Minister of Aviation. The new tunnel comprises air compressors, coolers, a working-section leg and evacuation plant, arranged in a closed circuit. Air at variable pressure, temperature and density is circulated through the working-section leg into which models with associated test equipment are introduced to enable their behaviour to be studied under various conditions of air-flow. In its present form with a fixed throat gap and contour nozzle, the tunnel is capable of giving nominal air speeds corresponding to Mach number 4, though a flexible-plate nozzle now under construction will enable a speed range of between Mach 2·5 to 5 to be obtained. It is of interest to note that the 8 ft by 8 ft wind tunnel commissioned at Bedford a few years ago had a maximum rating of Mach 2·8.

The complete working-section leg of the new tunnel, with all its associated servo-controls, was supplied by the G.E.C., the total value of the contract being over £1M. The working-section leg, which is illustrated opposite and shown in diagrammatic form in fig. 1, is over 154 ft long and comprises inlet and contraction sections, nozzle, bridle structure, model support section, supersonic and subsonic diffusers and an outlet section. In addition a calibration section for examining the air-flow pattern has been supplied; this unit is interchangeable with a model-support section in the line of the tunnel.

One of the principal design requirements has been to provide maximum availability of the tunnel for testing work. Since the rigging of a model with its instrumentation may take a considerable time, it must be possible for this to be undertaken outside the tunnel circuit, while tests are proceeding on another model. For this reason all the arrangements for the mounting, manipulation and instrumentation of models are incorporated in a number of separate and interchangeable model-support sections or trucks, which can be quickly disconnected and removed bodily from the air circuit to an adjacent rigging bay.

Another important feature of the tunnel is that the whole of the working-section leg is anchored at one point only, namely the model-viewing position, and both upstream and downstream of this point the various casings are mounted on wheels running on machined rails to allow easy opening of the tunnel for inspection and maintenance and to accommodate thermal expansion. In addition, provision is made for the model-support section, the two diffusers and the outlet section to be moved hydraulically some 11 ft downstream to allow visual examination of the model under test or the substitution of another model-support section. To enable this operation to be accomplished quickly, the appropriate flanges are fitted with hydraulically operated quick-release bolts of the interrupted-thread type which are actuated through two sequenced and interlocked control units. An electrically driven transporter trolley is provided to move the model-support sections from the tunnel position to the rigging bay and back.

The model under test can be viewed through windows in the side wall of the nozzle by means of a Schlieren system which is optically reflected back to the observation room. A television camera is also mounted in the Schlieren housing and is connected to a t.v. screen in the observation room.

MECHANICAL CONSTRUCTION.

Inlet and Contraction Sections.

A general view of the working-section leg from the inlet end is shown in fig. 2. The fabricated inlet casing is a pipe of progressively increasing diameter varying from 5 ft at the inlet to 9 ft at the settling chamber. The casing has a 90° bend at the inlet end, with built-in turning vanes at the corner, and the outlet end forms the outer housing over the settling chamber and screens which are carried on the contraction section. Both end flanges are fitted with double toroidal seal rings with a dry air supply fed in between them. This ensures the exclusion of atmospheric air when operating under vacuum, and forms a pressure seal under working conditions.

The settling chamber contains five stainless-steel wire mesh screen units supported in mild-steel shells which also serve as spacers. These units are bolted together to form a nest; silicone rubber pads between the jointing faces support the wire mesh and prevent fraying of the individual wires at the edges. This nest of screens protrudes from a flange on the contraction

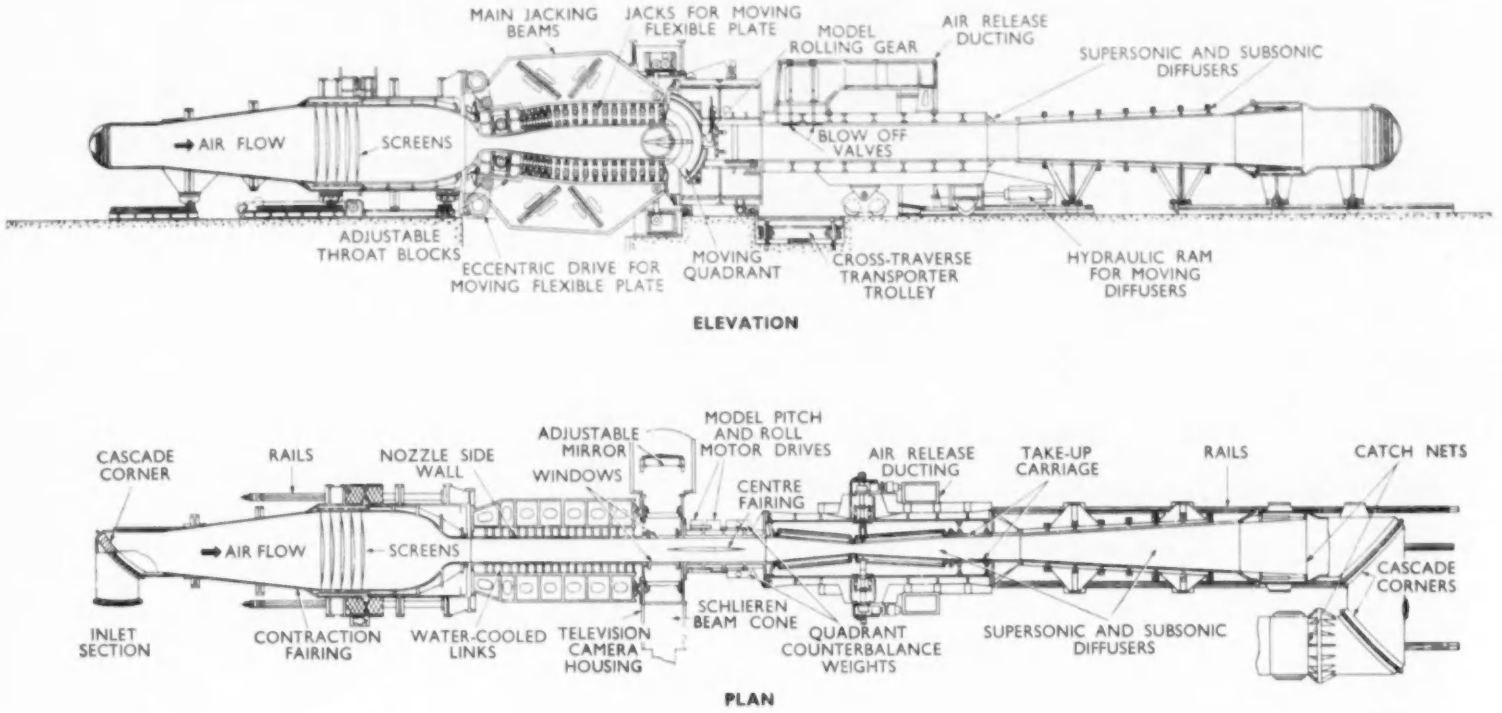


Fig.—1. Elevation and plan of the working-section leg of the wind tunnel.

fairing so as to be readily accessible for cleaning when the inlet section is moved upstream (fig. 3).

The contraction section consists of an outer cylindrical shell fitted with heavy stiffening rings and mounted on wheels to accommodate thermal expansion, together with an inner contraction fairing which transforms the cylindrical shape of the settling chamber to the rectangular 4 ft by 3 ft cross-section of the nozzle and ensures a streamlined air-flow.

NOZZLE SECTION.

To bring the tunnel into useful operation at the earliest possible time, a fixed-profile wooden nozzle operating at Mach 4 is being employed at present. The tunnel has, however, been designed to accommodate a variable-profile nozzle of the flexible plate type, and this unit, which is now being built, forms one of the most interesting aspects of the whole installation.

The maximum inlet pressure will be about 12 atmospheres absolute and, to prevent liquefaction in the nozzle at the higher Mach numbers, the temperature of the air will be allowed to rise to 150° C. Under some operating conditions the pressure in the tunnel may be below 0·1 atmospheric absolute. It was decided at an early stage that, with the high temperatures and high rates of change of temperature coupled with the degree of accuracy required for the nozzle control devices, it would be inadvisable to enclose these devices within a pressure shell.

This decision introduced the difficult problem of providing a very efficient sliding seal between the fixed and moving walls of the nozzle. The double seal to be used for this purpose will be packed with dry air to prevent the ingress of moist atmospheric air into the circuit. This system of dry-air packing of all seals has been employed on all joints in casings, and on all entries for drive shafts, etc., which penetrate the pressure shell.

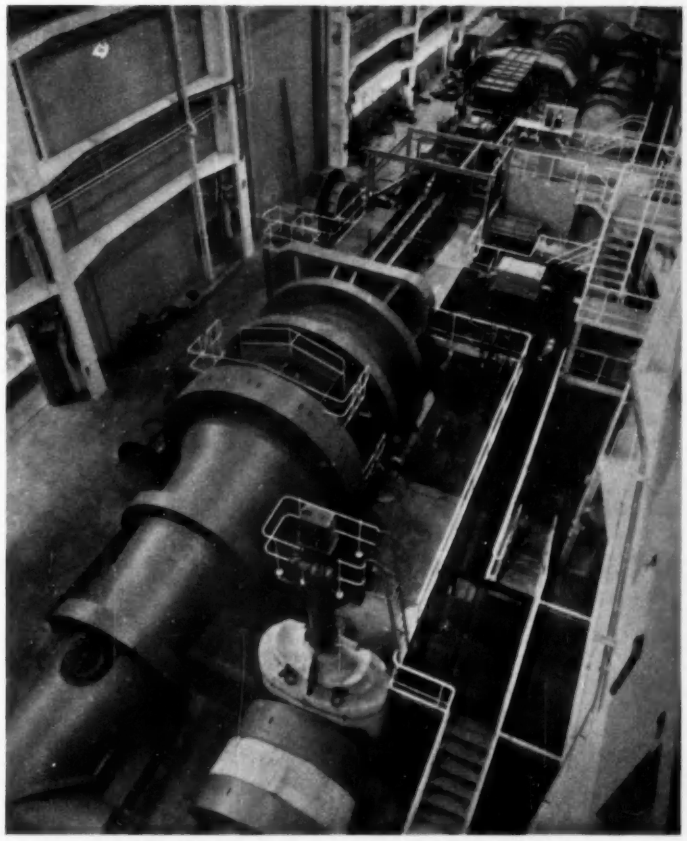


Fig. 2.—General view of the working-section leg from the inlet end.

Essentially the nozzle will comprise two fixed stainless iron side walls spaced 3 ft apart, with movable top and bottom walls of the same material. Each of the moving walls of the nozzle is carried by a pair of extremely stiff fabricated steel beams pivoted at the downstream end. At the upstream end each pair of beams carries a throat block of fixed contour which is driven upwards and downwards to vary the throat gap. The variable contour top and bottom walls of the divergent sections of the nozzle are formed by flexible plates each attached to one of the throat blocks at the upstream end and also to the supporting beams through 17 pairs of motor-operated ball screw jacks.

The information required to control the position of the flexible plate at the jack stations throughout the range of Mach numbers is provided by cams mounted on a sliding table in the nozzle controller. This is a separate piece of equipment located in a nearby room. When the operator selects a Mach number the sliding table is made to traverse a distance corresponding to the Mach number chosen so that the cams operate a number of sensing heads, each head driving a magslip coincidence transmitter. A magslip transmitter, mounted on an unstressed, constant-temperature gauge beam is directly connected to the flexible plate at each jack attachment point. The difference between the settings of the two magslips results in an error signal being set up which controls the necessary power to each jack motor to drive it, and consequently the flexible plate, to the position corresponding to coincidence of the two magslips. This

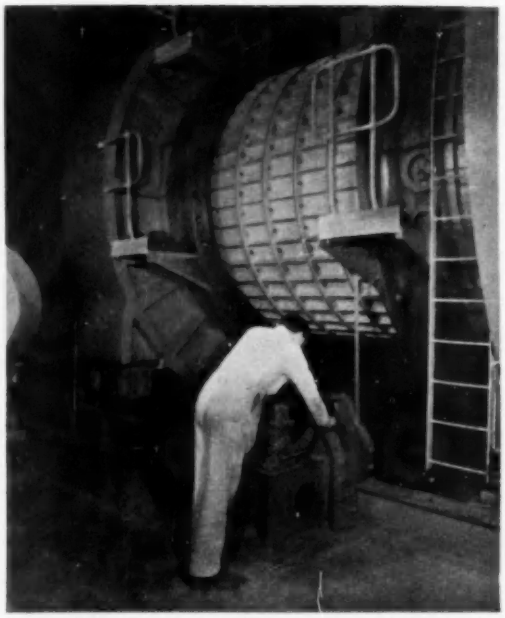


Fig. 3.—Placing the screens which smooth the air-flow in the inlet section of the tunnel.

system also compensates for temperature variations in jack length, and permits small corrections to be fed in by follow-through magslips as required.

Bridle Structure.

When the flexible plate nozzle is installed, its downstream end will be fixed into a bridle structure which is the only part of the working-section leg anchored to the foundations. Since the tunnel at present is operating with a fixed nozzle there is no necessity for the bridle structure, a temporary anchoring point having been made for the fixed nozzle. When the bridle structure is installed it will house the high- and low-temperature viewing windows, each with specialized illumination for use in conjunction with a remotely controlled television camera. The two windows on each side of the structure will be interchanged hydraulically. With the fixed nozzle only low-temperature viewing windows are required and use is made of the Schlieren viewing equipment already installed.

Model-Support Section.

Each model-support section (fig. 4) is a structure on which the model to be tested can be mounted and manœuvred in the airstream, and consists of four fabricated sections bolted together to form a rectangular shell with a polished, stainless steel, airswept surface. The model is mounted on a sting protruding from the end of the casing to line up with the viewing windows in the nozzle, and is carried in a quadrant which can be pitched about its centre to vary the attitude of model in the airstream within the limits of 5° depression and 27° elevation. Provision is also made for the model to be rolled through ±180° from a mean position irrespective of the position of the quadrant.

Both pitch and roll motions are provided by electric motors through load-limiting slipping clutches and reduction gearing, and are remotely controlled when the model-support section is in service. Portable control cabinets are provided to control the pitch and roll motions when the model-support section is in the rigging bay.

Calibration Section.

The calibration section (fig. 5) is similar in shape and dimensions to the model-support section with which it is interchangeable in the air circuit. The main difference is that the moving quadrant and sting are replaced by a probe housing which has a 2 ft traverse across the airstream. Inside this housing are two hollow probe arms carrying a common probe head fitted with pitot tubes and yaw meters. The probe head is capable of being moved 3 ft upstream and downstream of the window centre line, so that a plot of the air-flow can be made in the vicinity of the model.

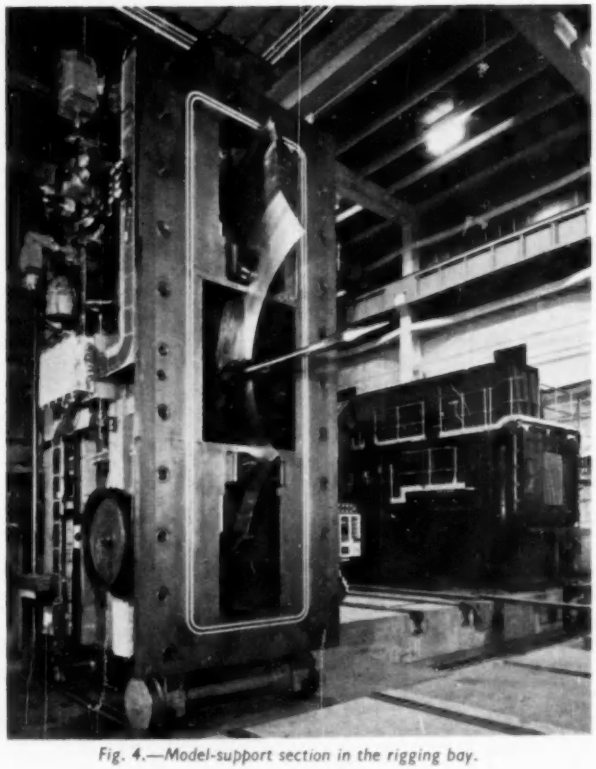


Fig. 4.—Model-support section in the rigging bay.

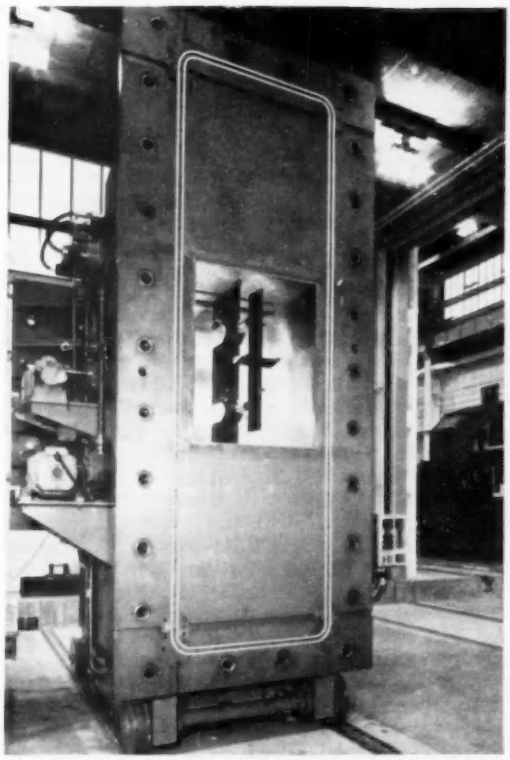


Fig. 5.—Calibration section, showing probe head with pitot tubes and yaw meters.

leakage across the throat, and are supported from the lower plate of the outer shell on a system of spring-loaded rollers.

Each moving panel system is operated by an electric motor, mounted on the side wall of the outer shell, and driving through suitable gearing a recirculating ball screw, which is attached to the back of the moving panels by links and guides. The thrust in either direction, generated by the airstream under working or emergency conditions, is carried by heavy thrust bearings mounted on the outer end of the recirculating ball screw shaft.

Two 22 in. diameter relief valves of the lightest possible weight, are mounted upstream of the throat on the top plate of the outer shell. These are designed to lift rapidly at atmospheric pressure and discharge through ducting which passes down each side of the diffuser casing, and thence through a channel in the foundations to atmosphere outside the building.

The complete diffuser is carried on a wheel-mounted undercarriage running on rails, and is aligned by guide shoes working on a massive guide rail. This undercarriage carries the hydraulic power unit for moving the entire downstream section of the tunnel.

Subsonic Diffuser Section.

The subsonic diffuser transforms the rectangular cross-section of the supersonic diffuser to a circular shape to match the outlet casing. It comprises a fabricated casing with longitudinal and transverse stiffeners, and at the downstream end is fitted with a catchnet to arrest any broken model which would otherwise be carried into the compressors. The

Supersonic Diffuser Section.

To obtain maximum operational efficiency of the tunnel, the speed of the air emerging from the nozzle is reduced, first by the supersonic diffuser and then by the subsonic diffuser, before being recirculated through the tunnel via the compressors. The supersonic diffuser (fig. 6) consists of a pressure shell of rectangular section, with top and bottom fixed plates which form part of the air-swept surface. Two systems of moving panels, hinged together and anchored at the upstream end, are carried on the sides of the shell to form a second throat. These moving panels and hinges carry p.t.f.e. - impregnated bronze seals along the top and bottom edges to prevent

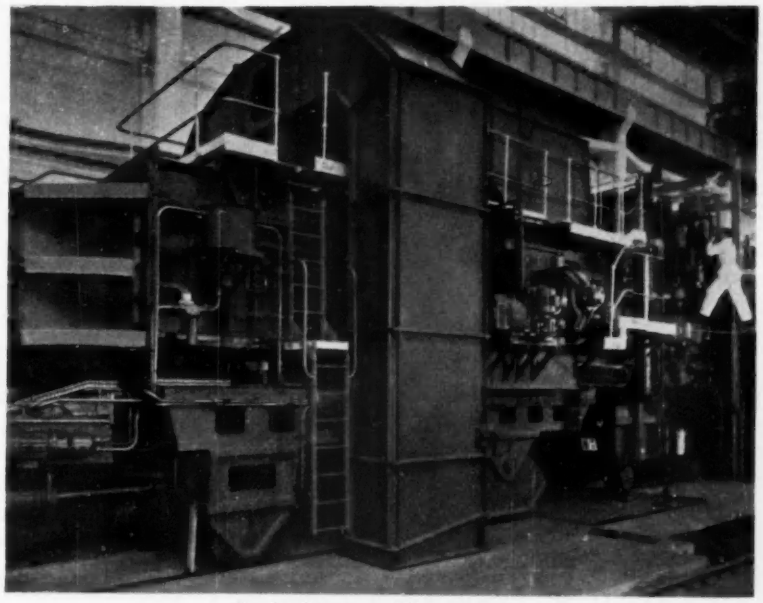


Fig. 6.—Supersonic diffuser section.

catchnet is formed from steel wire rope woven into a net of 2 in. mesh, and is fitted with spring tensioning devices to absorb the impact of moving objects.

Outlet Section.

The outlet section consists of a pipe 7 ft in diameter and fabricated into a U shape by means of two 90° bends each fitted with built-in turning vanes. The upstream end is increased in diameter to form a housing over the first catchnet, while the downstream end terminates at an outlet casing flange fitted with quick-release bolts to allow the tunnel to be broken at this point.

The outlet section is mounted on three wheels attached to feet on the underside of the casing, and alignment is maintained by guide rollers which run on a floor-mounted rail on the centre-line of the tunnel. This section also includes the mating flange and tail-pipe which is welded to the return pipe to the compressors. The return pipe houses a second catchnet, similar in design to the first, and also incorporates an alignment device to ensure correct positioning of the mating flanges when bolting-up the tunnel.

ELECTRICAL CONTROL SYSTEM.

The Nozzle Servos.

As previously mentioned, the desired air speed is produced by causing the air to pass through an aerodynamically shaped nozzle formed by flexible curved top and bottom plates suspended between fixed parallel side walls. The gap at the throat varies from 17 in. for a speed of Mach 2·5, down to 1·6 in. for Mach 5. The screw jacks which enable the flexible plates to be set precisely to the correct contour are servo-controlled, and it will be appreciated that the jacks must move in a co-ordinated manner to avoid any possibility of excessive local curvature and consequent undue stress in the plate. These co-ordinated movements are controlled by a specially developed machine, the nozzle controller. This consists of a heavy cast base carrying a table which can run lengthways on rollers. Bolted to the table are six rows of individually shaped cams, four rows having six cams each and two rows having seven cams each, arranged parallel with the direction of movement of the table (fig. 7).

Heavy portal frames, bolted and dowelled to the machine base, carry a corresponding array of cam-gauges. Each gauge incorporates a cam follower, moving vertically in recirculating-ball slides; the follower movement is transmitted by a high-precision rack and gear train to the rotor of a magslip coincidence transmitter mounted at the top of the cam gauge. Each magslip is the input element of a servo system controlling one pair of jacks; its rotation is compared with that of a second magslip connected through another precision rack and gear train to the back of the plate to which the pair of jacks is attached. By cutting the cam profiles to the correct shapes a movement of the table will cause all the jacks to move in the required relationship to one another.

The jacks must position the flexible plates to an accuracy of about 0·001 in. at any part of the 2 in. maximum range of travel; the maximum electrical error of any single jacking servo-system itself is less than half of this, i.e. the system will correct any misalignment between the cam gauge magslip and jack magslip exceeding the equivalent of about 0·0005 in. The remaining inaccuracies are due to the various mechanical components, such as gear errors in the cam gauge. One possible source of error, backlash in the gear trains driving the magslips, has been eliminated by the use of torque motors. These are small, two-phase a.c. induction motors, designed to give maximum torque at standstill. They are geared to the magslip rotors and energized so that torque is constantly transmitted through the gear train to the rack pinion and, in the case of the cam-gauges, presses the cam follower against the cam.

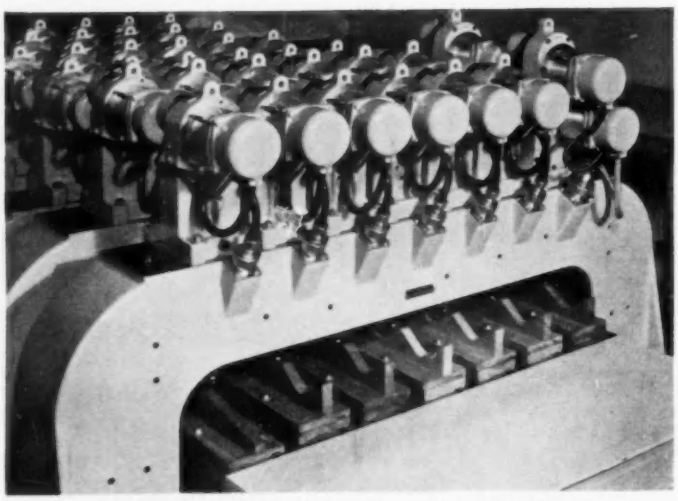


Fig. 7.—Cam gauges on the nozzle controller, with test cams fitted to the table.

With this method of simultaneously controlling all the plate jacks, the distance of the cam followers from one end of the 8 in. long cams is directly related to the Mach number for which the nozzle is set. This distance, which is the distance moved by the table from a datum position, has by design been made equal to the movement of the throat blocks, i.e. to half the throat opening. The servos which set the position of the throat blocks are controlled from magslips geared directly to the recirculating-ball lead-screw which moves the table. This leadscrew is also servo-controlled by the tunnel operator; the controlling magslips for this servo are contained in a preselector. This is a device which

enables the operator to select in advance the throat opening corresponding to the Mach number at which he wants the tunnel to operate.

The preselector is basically a gearbox of which the front face is a dial showing the distance of the throat blocks from the tunnel centre line. The pointers are geared to the magslips and to a small d.c. motor which is controlled directly from a knob on the panel just below the preselector. The operator can drive the preselector in either direction at any one of three speeds, enabling the preselector to be driven at high speed to near the required setting, slowed, and then moved at a crawl to precisely the required figure.

Having so set up the required throat gap, the operator will then energize the servo systems, which will cause the throat blocks and plate jacks to re-shape the nozzle, at a rate which the operator has also preset, until the new airspeed is attained.

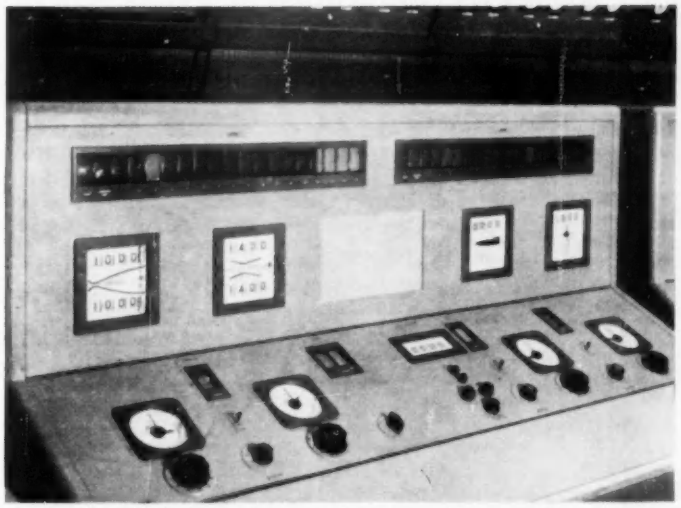


Fig. 8.—Control desk, showing the mimic indicators, preselectors and other controls for the throat, supersonic-diffuser and model-attitude servo systems.

Supervisory Instrumentation.

In order to provide a check on the operation of the servos controlled by the preselector, the operator has a mimic indicator giving a pictorial representation of the throat opening. This indication is provided very simply by two swinging bars, curved to represent the throat, which are each geared to a magslip of a type designed to produce torque. These magslips are energized by two other magslips geared directly to the respective throat blocks.

A digitizer system is also provided, and this gives a direct reading of the distances of the throat blocks from the tunnel centre line on two four-digit indicators housed in the mimic indicator casing. The digitizer heads are also directly geared to the throat blocks, being in the same gearboxes as the control magslips, with torque motors to eliminate backlash as in the case of the plate jacks. The digitizer heads each consist of four synchro-transmitters geared together (one synchro for each decimal digit to be displayed); the output voltages from these are suitably transformed and mixed and made to control bi-stable transistor circuits. These in turn control decoding relays which switch d.c. voltages to drive the M-type motors (12-position stepping motors) in the four-digit indicators; the numerals are displayed on the circumference of light cylindrical drums attached to the motor shafts. Further contacts of the decoding relays are used for the data recording system provided for the tunnel. A complete description of the digitizer system (which was specially developed for this application) is given elsewhere.*

A direct indication of the performance of all the servos is given by an error indicator connected to each servo amplifier; these indicators are mounted on the control desk. The indication consists of a horizontal black bar silhouetted against an illuminated rectangle; each indicator is controlled directly by the signal representing the difference in position between the control magslips of the associated servo. Thus when all the servos come to rest accurately in the desired position, the bars of all the indicators lie in the centre of the window; a failure of any servo to align itself properly would be shown by a displacement upwards or downwards of the bar.

The Supersonic Diffuser and Model Attitude Servos.

The jacks which operate the moving panel system of the supersonic diffuser are servo-controlled; the distance of the common hinge from the tunnel centre line may be varied from 8 in. to 17 in. and must be set to an accuracy of $\pm 0{\cdot}02$ in. Since the required hinge distance is related to the Mach number, the supersonic diffuser jack servos are also controlled from the nozzle controller, by means of two cams and cam-gauges. A further facility has been provided for the supersonic diffuser servos; control of them can be switched from the nozzle controller to a second preselector on the control desk, bringing them under direct control of the operator.

Two other important servos are those controlling the attitude of the model. The sting can rotate through 360° to roll the model, and this movement is controlled to give an accuracy of $\pm 0{\cdot}1°$. The quadrant can move vertically in an arc of a circle with its centre at the centre of the model, thus inclining the model to the airstream, and this movement is controlled to give an accuracy of $\pm 0{\cdot}05°$. Both these movements are set by preselectors on the control desk.

* T. Roberts: *Transactions of the Society of Instrument Technology*, **13**, 1, March, 1961.

The supersonic and model attitude movements are displayed to the operator by mimic indicators and digitizers in the same way as the throat block movements.

Details of the Servo Systems.

These servos and their inter-relationships may be represented by a block diagram (fig. 9). They are all basically the same, the differences which occur being due to the different sizes of the driving motors and the special requirements for some servos, such as preset speed control. Each servo consists of magslips controlling a d.c. generator through an amplifier; the generator in turn feeds a d.c. motor. Three sizes of motor are servo-controlled; the flexible plate jacks and nozzle controller and corrector are driven by $\frac{1}{4}$ h.p. motors, the pitch and roll movements of the model by 1 h.p. motors, and the supersonic diffuser and throat blocks by 6 h.p. motors. These are all reversible d.c. motors, separately excited at 110 volts, and with class H insulation, since heat developed in the tunnel, under some conditions of operation, will be conducted through the structure to the motors.

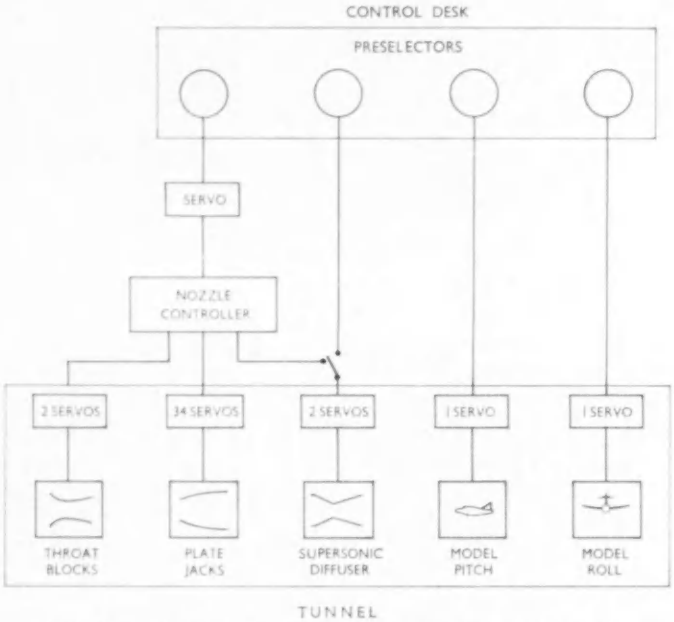


Fig. 9.—The working-section servo systems (the corrector has been omitted for clarity).

In considering the servos in greater detail, it is convenient to describe the supersonic-diffuser servo-system as a typical example (fig. 10). As mentioned earlier, the diffuser may be set automatically to correspond to any given Mach number, or it may be controlled directly by the tunnel operator using the diffuser preselector. The selected setting for the walls is shown by two pointers. The small inner pointer shows inches and tenths, and the outer pointer, making one revolution for each tenth of an inch, indicates hundredths of an inch to a high degree of resolution. The range of servo-controlled movement of each wall is from 8 in. to 17 in. and the combination of this range and required setting accuracy makes the use of coarse and fine magslips essential. The two transmitter magslips in the preselector are geared in a 10 : 1 ratio so that one makes 4·5 revolutions for the full range of pointer movement and the other makes 0·45 of a revolution. These magslips are connected to corresponding pairs of magslips, two for each wall and geared in the same ratios, which are rotated by the movement of the diffuser walls, through precision, minimum-backlash gearing driven by racks mounted on ball-slides. Thus the magslips form coarse and fine error signal chains for both walls and use common transmitters. Alternatively, to control the diffuser from the nozzle controller the magslips linked to the walls are connected by a multi-pole changeover switch to the cam-gauge magslips; the two gauges (which may be seen on the right of the controller in fig. 7) each have a coarse and a fine transmitter magslip suitably geared, so that in this case there are separate pairs of coarse and fine chains for the two walls (see also fig. 10).

As usual for magslip systems, the angular settings of

the magslips are such that when the walls are at the dimension set on the preselector or correspond to the height of the cams, as the case may be, the output voltage from all four chains is zero. When the preselector or nozzle controller is moved, a signal voltage is generated in the chains which is proportional to the angle through which the preselector or cam gauge

When an error signal is fed to the amplifier the current increases in one field winding and decreases in the other, producing a net flux which is nearly proportional to the magnitude of the signal up to the saturation level of 1·5° angular misalignment of the magslip chain. The direction of the resultant flux depends on whether the error signal is in phase or anti-phase with the

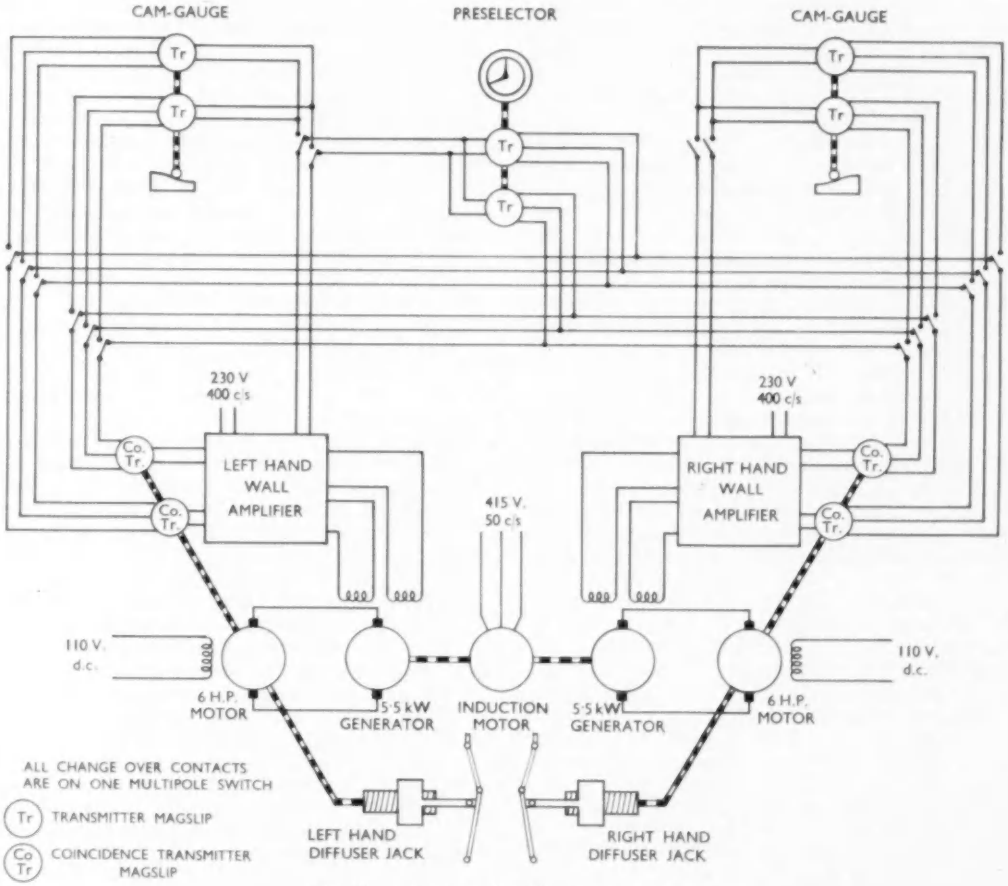


Fig. 10.—The supersonic-diffuser servo system.

magslip rotors are turned. The signals from the magslip chains for each wall are fed to an amplifier; if the preselector or cam-gauge movement corresponds to less than about 100″ rotation of the fine magslip, then the error signal from the fine chain controls the amplifier, but if the movement is greater than this, then a relay transfers the control to the coarse chain, until the misalignment has been reduced to 100″ or less.

The amplifier is double-sided; each side controls a field winding of a 5·5 kW d.c. generator. With no input signal to the amplifier, each field winding has a current of 0·75 A flowing in it, producing magnetic fields in opposition, so that no voltage is generated.

supply to the magslip transmitter; this supply is derived from a transformer on the amplifier chassis. For zero error signal, the two sides of the amplifier are maintained at half their maximum output by biasing voltages derived from the same transformer; the error signal voltage is added to one bias and subtracted from the other, according to its relative phase. The resultant signals are rectified and amplified to excite the generator fields, as described above. The relationship between generator field currents and magslip angle for steady state conditions is shown in fig. 11: generator voltage magnitude is also indicated.

The plate jack servos are the simplest; they use only

one magslip chain, and the servo amplifiers feed the fields of 0·28 kW generators. In their normal mode of working the plate contour is determined by the cams and any small modifications to the contour, which may be needed for different air pressures, etc., would mean cutting new cams. This has been overcome by providing a follow-through magslip to be connected between the transmitter magslip geared to the jack and the coincidence transmitter magslip on the cam-gauge. These follow-through magslips are operated by a second set of cam-gauges, mounted on a machine known as the corrector, which is rather like the nozzle controller, and serves to provide a co-ordinated set of corrections for modifying the plate profile to match different tunnel operating conditions. The cams on the movable table of the corrector consist of inclined bars which are hinged at one end so that their slopes may be set to predetermined angles. With the corrector table at one extreme of its travel, the cam followers are in line with the hinges of the bars, and the follow-through magslips are in their datum, or zero, positions; they can then be switched into or out of circuit as required. When corrections are required, the bars are set to the required slopes, the magslips switched into circuit and the corrector table moved to the other end of its travel. In this way all the corrections are set in simultaneously and smoothly; their magnitudes are shown on a set of dial indicators on a panel in the observation room.

The model pitching and rolling servos, like the diffuser, have coarse and fine magslip chains, but use 1·1 kW generators. An additional feature of these two servos is the requirement for steady traverse under precise speed control, calling for a continuous range of preset speed from the full speed of 1°/sec. of pitching, or 2·5°/sec. of rolling, down to one-tenth of these speeds. In addition, these servos should preferably be 'dead-beat', unlike those already mentioned where a limited transient overshoot on initial alignment is permissible.

In the case of the throat and nozzle controller servos, the high accuracy combined with the range of movement makes the use of three magslip chains necessary, the magslips being geared in the ratios 100 : 10 : 1. The coarse chain magslips make 0·4 of a revolution for the full 8 in. travel of each throat block and the controller table. The throat block servos also are not required to be dead-beat, but the nozzle controller servo is; the latter is speed controlled in a similar manner to the model attitude servos (full speed is 4 in./min) and the acceleration and retardation of the table are limited to permit the jack servos to respond without excessive following errors.

The Servo Amplifiers.

The amplifiers are of some interest in that transistors are used throughout, together with a number of semiconductor diodes. The d.c. amplification is provided by three or four emitter-coupled stages (according to the servo), the careful design of which has resulted in a performance which is independent of variations in transistor characteristics within normal production tolerances, and which is also very little affected by any change of ambient temperature in the room where the equipment has been installed. The basic amplifier is that used for all the plate jack servos, with three stages of d.c. amplification on each side, using a supply of 24 volts. Each of the other servos uses this basic amplifier coupled to a 'modifying unit' which is individual to the particular servo. This unit contains all the other special circuits needed, such as the coarse/fine magslip chain switching, speed control and special feedback circuits. In the case of the model attitude, supersonic diffuser and throat block servos, the modifying unit also contains the fourth d.c. amplifying stages necessary for the fields of the bigger generators. This stage is supplied at 35 to 60 volts (depending on the servo), and uses two power transistors working in parallel to feed each field; each of these transistors with its special mounting arrangement is capable of dissipating 11 watts at maximum room temperature. The maximum power fed into a 5·5 kW generator field by a pair of these transistors is 50 watts.

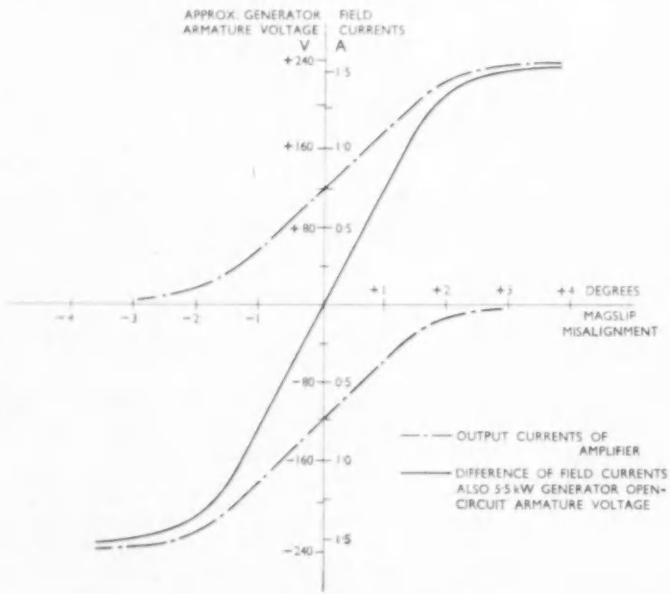


Fig. 11.—Servo amplifier characteristic.

Servo Stability.

In any servo system the question of stability is an important consideration. A major factor in the stability or other-

wise of a system is the inertia of the load (including the drive). In the case of all the servos described in this article, the very large reduction ratios in the drive gearing make the inertia of the load negligible compared to that of the motor itself. A transient velocity feedback is used for some servos (e.g. the plate jacks and diffuser): it is derived from the output voltage of the generator: that is, a feedback current is fed to the amplifier only when the generator voltage is varying.

As already mentioned, the supersonic diffuser walls are required to be positioned to an accuracy of ±0·02 in. in a travel of 9 in. so that in order to allow for manufacturing tolerances the servos are designed to produce the required output torque for an error of 0·005 in.; this result has been achieved without difficulty. The throat block servos, though similar to the diffuser servos, are required to have an accuracy some ten times better, with a correspondingly greater problem in achieving stability. The feedbacks required are stronger and more complex, since degradation of the performance in any way must be avoided; they are derived from tachometer generators geared to the driving motors. The nozzle controller and pitching and rolling movement servos also use tachometer generators, principally in their case because of the speed control requirement.

The Motor-Generator Sets.

The generators are housed in a room provided for the purpose at one side of the wind tunnel building. Since the various servos fall readily into pairs, the corresponding pairs of generators have a common driving motor. The two pairs of 5·5 kW generators for the supersonic diffuser and throat block servos are driven by 18 h.p. 3-phase induction motors. A third set of identical design has been provided as a standby which may be quickly connected into circuit in place of either of the other sets by changeover links. The two 1·1 kW generators of the pitch and roll servos are driven by a 3·5 h.p. induction motor; a second similar set provides power for the movement of an airstream calibration probe, which can be inserted into the tunnel in place of the model-support section; and, as with the bigger sets, a third set forms a standby for either. A fourth set is installed for use with a model-support section in the rigging bay, to which it can be connected via a jumper from sockets on junction boxes in the rigging bay. The pairs of plate jack generators are driven by 1 h.p. motors; these are laid out in a row below the control platform.

The special supplies, of 230 V, 400 c/s single-phase used by the servo amplifiers and digitizers, and 110 V d.c. used for the motor fields and a considerable part of the control and interlocking circuits, are produced from motor-generator sets sited alongside the servo generators. The 400 c/s supply is provided by a 30 kVA alternator driven by a 27 h.p. induction motor and is controlled by an automatic voltage regulator which holds the voltage to ±2·5% for variations of from one-quarter to three-quarters of full load. A 12·5 kW generator driven by a 20 h.p. induction motor provides the 110 V d.c. supply. Both these sets also have duplicate stand-by sets, with link boards to facilitate the changeover of connexions.

Interlocking and Protection.

All the motor-generator sets are started direct-to-line through contactors, with the usual h.r.c. fuse and overload cut-out protection; electrical interlocks prevent any set being started on load and ensure starting operations being carried out in their correct sequence. As the first step, the amplifiers are connected to the 400 c/s supply, but the connexion is not completed unless cooling fans installed in the amplifier cubicles are running. Relay circuits in each amplifier detect any absence of internally derived supplies (and also whether or not the connexions to the amplifier are properly plugged in). The fields of the servo motors are then switched on; each motor has a field failure relay, the 'make' contacts on all such relays being connected in series. Satisfactory operation of the appropriate field failure relays energizes the contactors controlling the motors of the m.g. sets (the generator armature circuits are open). At this stage certain fault detection circuits, which 'lock' to the fault condition after occurrence of a fault or interruption of supply, must be reset. These include plug interlock circuits which check that all servo components such as magslips are properly plugged in, and limit switch circuits which ensure that no servo-driven member can attempt to overrun its mechanical limits. Only when all the related fault circuits have been cleared, the amplifiers concerned are giving a clear indication, and the m.g. set for the servo is running, can the servo finally be energized by closing the common armature circuit of the generator and motor. Here also protection is provided by an overload trip with contacts in the armature-loop contactor circuit.

The relays and contactors which carry out the switching and interlocking are housed in cubicles on the control platform in the motor-generator room; signal lamps on one of the cubicle front panels show the state of all the fault circuits and m.g. set motor contactors, so that the state of circuit excitation can be seen at a glance and any fault quickly located.

Acknowledgements.

The authors are indebted to the Chief Engineer, Ministry of Works and to the Director, Royal Aircraft Establishment, Ministry of Aviation, for permission to publish this article and its accompanying illustrations.

First 400 kV Oil-filled Cable in Great Britain

In anticipation of the need for oil-filled cables suitable for the transmission of power at 400 kV, Pirelli-General has designed and submitted for type approval a complete cable system for operation at this voltage. Details of this cable, together with a description of the new laboratory which has been built to provide the appropriate testing facilities, are given in this article.

THE need for transmission of increasing quantities of electrical power has resulted in a steady increase in the operating voltage of transmission lines throughout the world. This upward trend has so far reached higher values of voltage abroad than in this country but the recent proposal by the Central Electricity Generating Board to up-rate existing 275 kV lines to 400 kV will bring Great Britain into the forefront of progress in this field.

In anticipation of the need for cables at this voltage level, Pirelli-General has designed and submitted for type approval a complete cable system for operation at 400 kV. The cable is of the low-pressure oil-filled type and is designed on the same basis as the oil-filled cable system for lower voltages which has proved its complete reliability in service over many years.

A complete range of accessories is available for use with the 400 kV cable and these consist of an outdoor sealing end, an oil-immersed sealing end whereby the cable can be terminated in the entry chamber of a transformer, a straight-through joint and a stop joint.

The cable has an overall diameter of 4·10 in. and is of the single-conductor hollow-core type (fig. 1). A 3-phase circuit comprising three cables laid side-by-side in the ground with a spacing of 12 in. centres would have a continuous power transmission capacity of 528 MVA to 675 MVA over the normal range of soil thermal resistivity. This is equivalent to the entire output of a large modern generating station.

The dimensions of the cable are shown in Table 1 and the technical details are outlined below:

Conductor cross section	0·9 in²
Maximum stress at working voltage (nominal)	160 kV/cm
Insulation thickness (minimum) ...	0·90 in.
Impulse voltage withstand level ...	1400 kV
Maximum continuous conductor temperature	85° C
Capacitance per 1000 yards ...	0·188 μF
Charging current per 1000 yards ...	13·6 A
Typical current rating for three cables laid side-by-side with 12 in. centres at a depth of 3 ft 6 in.	
In soil of g = 120° C/watt/cm ...	760 A
In soil of g = 60° C/watt/cm ...	975 A

The type test series followed the pattern already established for cables up to 275 kV; the tests carried out were:

(1) Power-factor/voltage test at ambient temperature up to twice the working voltage.
(2) Bending test, followed by a voltage test for 15 minutes at 425 kV.
(3) Measurement of thermal resistivity.
(4) Mechanical test on sheath reinforcement; 7 days at 150 lb/in².
(5) Loading cycle test, 20 daily cycles to 90° C-100° C conductor temperature, with 308 kV applied continuously.
(6) Thermal stability test, 6 hours at 95° C and 308 kV.
(7) Impulse withstand test.

Tests 5, 6 and 7 were carried out on the same assembly, which included the full range of accessories.

Fig. 1.—400 kV 0.90 in² single-core oil-filled cable.

The impulse withstand test which concluded the series was carried out in the presence of a large gathering of engineers representing the Central Electricity Generating Board, Area Boards and the major Consultants, in the new High Voltage Laboratory of the Engineering Department at Eastleigh (fig. 2).

Testing commenced at 1400 kV, the declared withstand level, and after the application of 10 negative and 10 positive impulses at this level the voltage was raised in 50 kV steps to 1600 kV, with 10 negative and 10 positive impulses at each level. The test was concluded at 1600 kV without breakdown of the assembly.

TESTING FACILITIES.

The laboratory in which these tests were carried out was built to provide improved facilities for the development and type-testing of new designs of high-voltage cable and accessories, thus enabling Pirelli-

TABLE 1.

	Diameter mm
Oil duct	8
Steel spiral	9·02
Conductor	32·9
Conductor screen c.b. paper	33·8
Insulation w.p. paper	81·2
Insulation screen c.b. paper interlocked with perforated metallized paper	81·75
Lead alloy sheath	88·36
Impregnated cloth tape	
Six plain copper wires longitudinally applied	
Impregnated cloth tape	
Two h.d. tin-bronze tapes 0·75 in. × 0·006 in. in parallel	89·89
Serving overall	104·27

General to maintain the rate of technical progress so important in the highly competitive conditions existing in the cable industry today. This work has become increasingly important in recent years as improved materials and manufacturing methods have enabled cables to be designed for higher stresses and operating voltages than ever before.

The new laboratory utilizes the test equipment already available, with some additions, but affords greatly increased space and improved working conditions. For work of the kind envisaged, floor space is one of the most important requirements. An experiment, for example, on a new design of 132 kV 3-core straight joint, requires the erection not only of the joint itself but also of six sealing ends and two splitter boxes, requiring an area of at least 1500 ft². If the test in question is a type test on a new design of cable, it is usually necessary to include in the test assembly each type of accessory intended for use with the new cable, and the floor space required becomes even greater. Moreover, such tests may continue for weeks or months, and in some cases as much as twelve months, before approval of the new design is given. If work is to continue on a number of projects simultaneously, the importance of adequate floor space becomes evident.

A second important requirement is adequate height. In order to test cable systems for the highest voltages in use today, impulse voltages of 1·6-1·7 million volts are required, and even higher voltages may be needed in the future. The impulse generator itself is 26 ft high and the roof of the building must be of such a height that an adequate clearance is available between the top of the generator and the roof.

The new laboratory building meets these requirements with a floor area of 13 500 ft², and the height to the apex of the roof of the main test bay is 60 ft. This not only allows adequate clearance at present but provides for the addition of a further stage to the impulse generator. The building is divided into two bays, the larger of which is 125 ft. long by 70 ft wide. This bay is used for the highest voltage testing and is of portal frame construction, thus eliminating roof trusses. The height to the apex of the roof is 60 ft and the height to the eaves 57 ft. The smaller bay is 70 ft by 65 ft and has a pitched roof with a height of 32 ft to the eaves. Both bays are steel framed with aluminium sheeting and an insulating lining. The floor is of red quarry tiles in order to avoid the dust inevitable with a concrete floor.

Lifting facilities in the larger bay are provided by a 2 ton crane with a maximum height from hook to ground level of 48 ft and capable of passing over the highest test equipment in the laboratory. The smaller bay is equipped with a 1 ton crane with a maximum height of 27 ft to the hook.

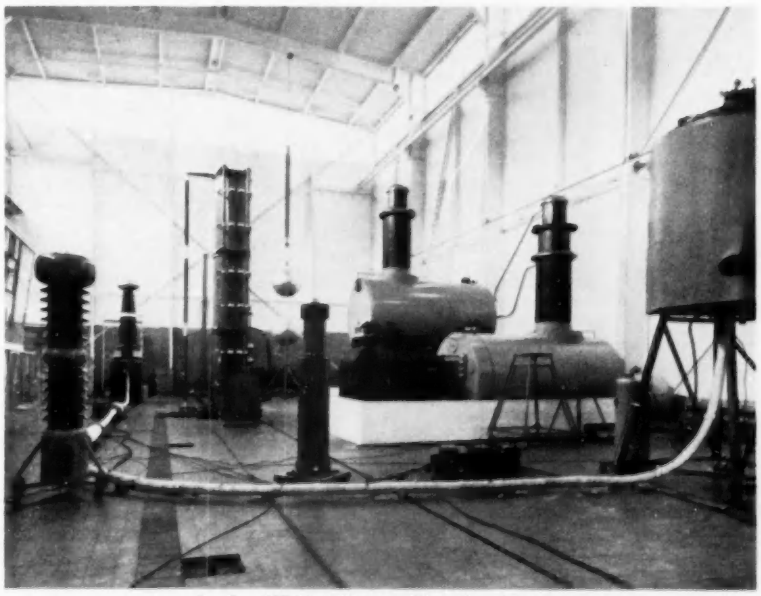


Fig. 2.—400 kV cable assembly undergoing tests.

All the major items of test equipment are controlled from a central control room (fig. 4), situated between the two bays at a height of 8 ft above the laboratory floor. The control room is fitted with plate glass windows extending practically to floor level and sloping outwards from the floor, so that an almost uninterrupted view of the whole of the laboratory can be obtained.

The building is lighted by windows placed high in the wall around three sides of the main bay and by north-facing roof windows in the smaller bay. Artificial lighting is provided by eight 400 watt mercury-vapour lamps placed on the walls of the main bay just below the window level, and by eight smaller lamps suspended from the roof of the smaller bay. The decision to place the lamps on the wall of the high test bay was taken in order to simplify replacement of lamps, which would become a major problem for equipment on the roof 60 ft from floor level. Both bays are heated by a unit type, oil-fired warm air heater with a capacity of $1\frac{1}{2}$ million B.t.u.'s per hour.

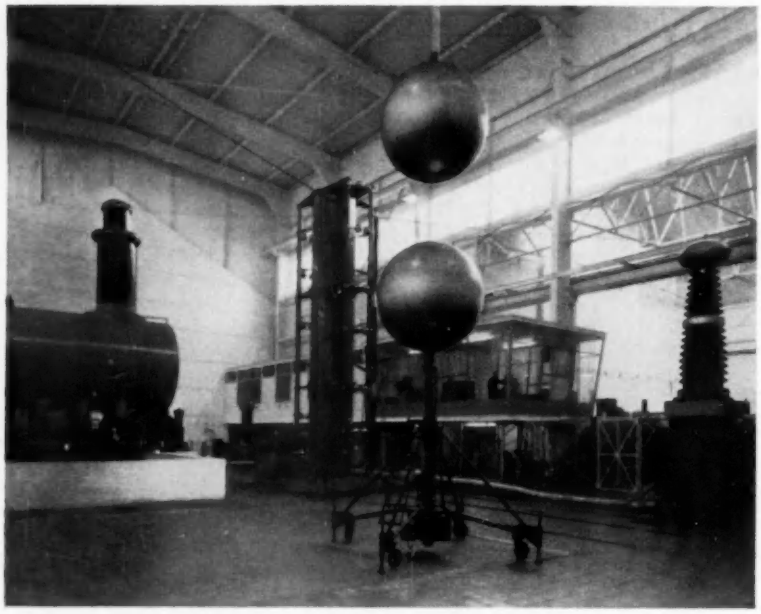


Fig. 3.—Main bay of the high-voltage laboratory.

The most important items of test equipment for cable testing and development work are the impulse generator and high-voltage alternating-current testing transformer; each bay of the new laboratory is equipped with both of these items. The larger bay contains an impulse generator with an open-circuit surge voltage of 2·4 million volts and a surge energy of 57 kilowatt seconds. This generator is of somewhat unusual design in that all the capacitors are contained in a central column of bakelized paper, and is of comparatively small size in relation to its output. The well-known Marx circuit is employed having twelve stages charged to a maximum direct voltage of 200 kV from a mechanical rectifier. The generator is on rails and is movable to four alternative operating positions, thus allowing the maximum flexibility in the layout of test assemblies. The impulse voltage wave is monitored by means of a resistance-capacitance voltage divider and transient recorder, with facilities for visual examination and photographic recording of wave shape.

High-voltage a.c. testing in the large test bay is carried out by the use of two 500 kVA 333 kV transformers, one of which is insulated from earth for 333 kV. A maximum output voltage of 666 kV can therefore be obtained by means of a cascade connexion. These transformers are also used for power-factor tests by the Schering bridge method using a standard capacitor of the compressed-gas type of 100 picofarads capacitance and suitable for use up to 500 kV.

Voltage measurement in this bay is by means of a 1·5 metre diameter sphere gap. The upper sphere is suspended from the roof and can be lowered by a winch to permit the crane to pass. Two alternative positions are provided for the sphere gap.

In the smaller bay of the laboratory there is a further 800 kV impulse generator, consisting of four 200 kV stages and with a total surge energy of 22·4 kilowatt seconds. High voltage a.c. testing is catered for by a 300 kVA 150 kV transformer and a further 30 kV 100 kVA transformer. A 50 cm sphere gap is used for voltage measurement in this part of the laboratory and a 100 kV 100 picofarad standard capacitor is available for power-factor testing.

It is frequently necessary to heat the conductor of cable assemblies undergoing test, and this is done by providing a link between the terminations of the cable so that the cable conductor forms part of a closed loop.

Fig. 4.—Interior of control room.

The complete cable passes through the yoke of suitable step-down transformers and a current is induced in the cable conductor by this means. A total of 275 kVA, controlled by two induction regulators and available at five separate points in the laboratory, is used for the supply to these heating transformers.

Thermal resistivity is an important characteristic of cable insulation and is measured by passing a constant direct current through the cable conductor and making careful measurement of temperature drop through the insulation. The current supply required for this test is provided by a motor-generator with a capacity of 30 kW and a maximum current output of 3000 amp.

To ensure safety of personnel, an elaborate system of interlocking is provided between the control systems of the test equipment and the gates and fences of the test area. Portable fences are used to surround the test assemblies to ensure the maximum flexibility in layout of the tests and these fences are coupled by plug and socket connexions to one another and to points on the wall of the laboratory, so that the breaking of any of these plug-in links will automatically remove the test voltage.

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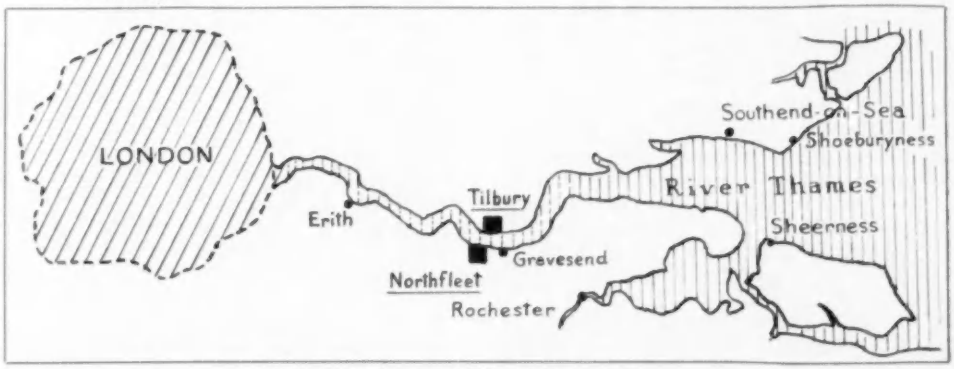
350 MW Turbo-alternators for Tilbury B Power Station

The G.E.C. is to build four 350 MW turbo-alternators for the Central Electricity Generating Board, the value of the order being in excess of £8 million. The sets are for the installation in the Tilbury B power station, Essex, situated on the north bank of the River Thames.

Each 3000 rev/min turbine will be of the tandem compound type having operating conditions at the turbine stop valve of 2300 lb/in² and 1050° F, with reheat to 1050° F and exhausting at a vacuum of 28·9 in. Hg. Generation will be at 20 kV and the alternators will have water-cooled stator windings and direct hydrogen-cooled rotor windings. The first two turbo-alternators are scheduled for commissioning in 1965 and the remaining two in 1966.



Map showing location of Tilbury B Power Station.

Corona Discharge Voltage Stabilizers

By R. O. JENKINS, A.R.C.S., D.I.C., Ph.D., F.Inst.P.,
Hirst Research Centre.

INTRODUCTION.

IT is only relatively recently that the corona type of gas discharge has been applied to voltage stabilization. For a considerable period now the glow discharge stabilizer tube has been a standard component in electronic equipment, and has provided a stable reference voltage in a large variety of power packs. Such tubes, however, operate at a voltage usually in the neighbourhood of 100, and with currents in the range of a few mA up to about 100 mA.

There are various applications nowadays requiring stable voltages up to a few kV where the current to be supplied is only 1 mA or less. The glow type of gas discharge is clearly not suitable for this type of application, whereas the corona discharge can be made to operate in these ranges of voltage and current.

PROPERTIES OF THE CORONA DISCHARGE.

Most engineers visualize a corona discharge as an undesirable phenomenon consisting of luminous discharge streamers leaving a high-voltage conductor, usually from a point or discontinuity. This is, however, only one particular form of the corona type discharge. A corona discharge takes place between two electrodes when one of them has a shape which concentrates a high electric field near its surface. If the potential difference between the two electrodes is sufficient, stray ions already present in the high-field region acquire sufficient energy between collisions with neutral gas molecules to ionize them, and a charge avalanche builds up. If the field is increased slightly the ionization spreads over the electrode surface where there is the high field, and appears as a faint luminosity. It is this form of the corona discharge which has the characteristics desirable for voltage stabilization. If the discharge current is increased above a certain value then the streamers begin to occur and finally a spark breakdown takes place.

For voltage stabilization it is required that the voltage drop across the discharge shall remain sensibly constant over as large a current range as possible. It is found in practice that the best way of achieving this is to have a cylindrical cathode with an axial wire anode. The discharge then has the form shown in fig. 1. The main voltage drop is in the ionizing region and is almost independent of current. The current actually varies as a very high exponent of the voltage drop across the ionizing sheath. The outer positive ion region acts as a positive impedance, which is usually called the incremental resistance. For voltage stabilizing this resistance should be as low as possible. The resulting current/voltage characteristic is shown in fig. 2. As the current increases the incremental resistance tends to zero. Streamer formation then begins and the discharge suddenly changes to a thin glowing streamer reaching between the electrodes with a lower voltage drop than the corona discharge.

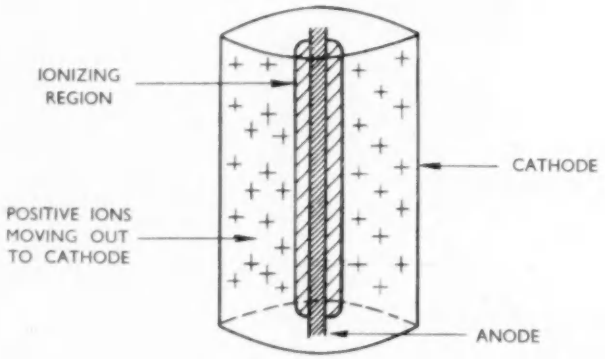


Fig. 1.—The corona discharge.

It is found in practice that hydrogen is the best gas to use for the corona stabilizers as its relatively lightweight ions are more mobile and this gives a lower

incremental resistance. In addition hydrogen supports a higher current in the desired discharge mode than any of the other gases, some of which form streamers at quite low currents. In order to ensure the necessary concentration of the field round the anode, its diameter must be small compared with that of the cathode and is usually about $^1/_7$ of the latter.

The voltage of the discharge increases with the diameter of the electrodes, and in a given electrode system is approximately proportional to the gas pressure. It is thus possible to make corona stabilizers covering quite a large range of voltage by filling similar tubes with different pressures of hydrogen.

manufacture is therefore to ensure good purity of the hydrogen filling. Another important point is that hydrogen is very easily absorbed into the tube materials, particularly the cathode, during operation. The cathode must, therefore, be made of a suitable alloy and pretreated to reduce this absorption to a minimum. The tubes are given an ageing process during manufacture, by operating at a fairly high current for about 100 hours. This stabilizes the gas pressure and the voltage to its final value. The resulting stability during life for a typical 1 kV SC1 tube is illustrated in fig. 4.

One other feature of interest is the reduction of time delays in starting the discharge. It has been seen that

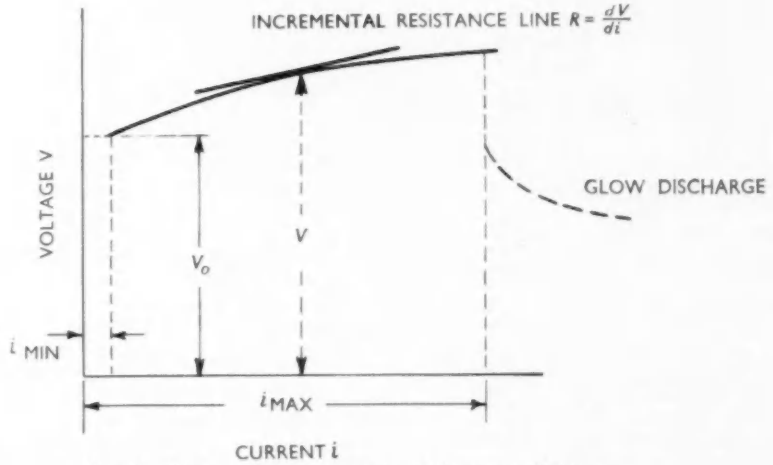


Fig. 2.—Current-voltage characteristic of the corona discharge.

G.E.C. CORONA STABILIZER TUBES.

The G.E.C. has developed a range of corona tubes embodying the general principles just explained. These tubes are shown in fig. 3. It will be seen that they have cylindrical cathodes with the axial anode wire located by ceramic insulators which close the ends of the cathode. The types SC1 and SC3 are filled with various pressures of hydrogen to cover a voltage range of 350-2000. The SC3 is intended for portable equipment where space is at a premium and the operating currents are only of the order of 100 μA, while the SC1, with a standard B7G valve base, is for more general use. A standard range of voltages of 350 V, 400 V and upwards in 200 V steps is made. The SC2 and SC4 types are both mounted on B9A valve bases and cover voltage ranges of 2·5-4·5 kV and 5-7 kV respectively, the former in 500 V steps and the latter in 1 kV steps. All the tubes can, of course, be specially 'tailor made' to other voltages within these ranges by choosing the appropriate hydrogen filling pressure.

The voltage for a given current in a particular tube is only a function of the hydrogen pressure, providing that the hydrogen is pure. One important point in

the start of the discharge depends on the presence of stray ions in the discharge space. These ions are formed by cosmic radiation and stray radioactivity, and are lost quite quickly by recombination. In low-voltage tubes where the unstabilized supply voltage is not much above the operating voltage there may be considerable delay before the corona discharge can form, as the ions are lost before initiating the discharge. This is avoided in the SC1 and SC3 tubes by the inclusion of some thorium oxide on the insulators.* This compound is slightly radioactive (some orders less than the average luminous wrist watch) but provides sufficient ions to ensure quick striking of the discharge.

METHOD OF USE.

The tubes are generally used in the simple shunt stabilizer circuit shown in fig. 5(*a*) with its equivalent circuit in fig. 5(*b*). The unstabilized voltage is usually arranged to be about 20-50% above the tube voltage, and the series resistance in the range of 1-10 megohms. It can easily be shown that the stabilizing ratio

* G.E.C. Patent Application No 20864/58.

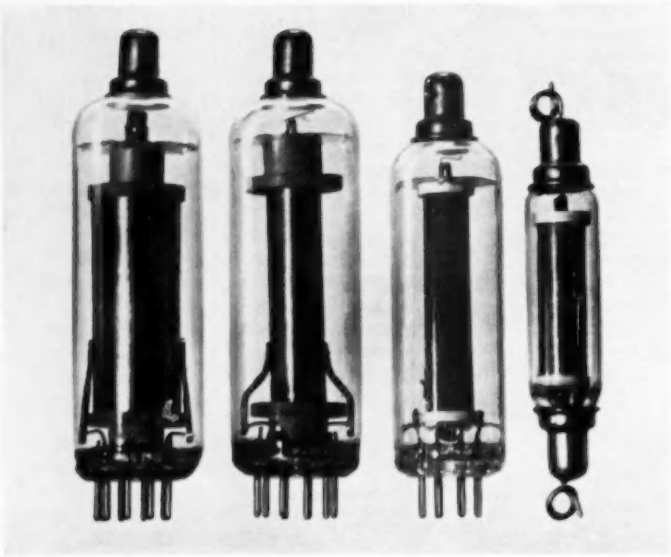


Fig. 3.—The G.E.C. range of corona discharge voltage stabilizers. Left to right: SC4, SC2, SC1, SC3.

obtained, i.e., $\frac{dV_1}{dV_2}$ is approximately equal to $\frac{R_t}{R}$ where R is the incremental impedance of the tube. For most applications the current through the tube will be of the same order as that through the external circuit. Variations in the load current can thus be taken up by corresponding variations in the tube current. Care must, of course, be taken to ensure that the variations due to changes in unstabilized supply voltage added to those due to changes in load current do not cause the current through the corona tube to become too small or to exceed the maximum stable corona current.

Typical maximum and minimum currents and incremental impedances for various tubes are shown in Table 1. The impedances vary with the actual operating current, and also depend somewhat on the method of measurement, particularly for the high-voltage tubes.

The maximum continuous current of 100 μA for the SC3 is to ensure voltage stability during life. The value

TABLE 1.

Tube Type	Voltage	Minimum current μA	Maximum peak current μA	Maximum continuous current μA	Incremental resistance in ohms at normal operating point
SC1	400	1	500	500	15 000
	1000	11	650	650	30 000
	2000	16	900	900	120 000
SC3	400	1	400	100	25 000
	1000	9	500	100	50 000
	2000	11	650	100	200 000
SC2	2500	25	1750	1000	100 000
	3500	25	1750	1000	130 000
SC4	5000	25	2000	1000	200 000
	7000	25	2000	1000	250 000

of 1000 μA for the SC2 and SC4 is necessary to avoid thermal effects which tend to reduce the peak current in the corona discharge mode. From the values shown in the table it can be seen that stabilization ratios in the range of 10-100 are achievable. A typical example of

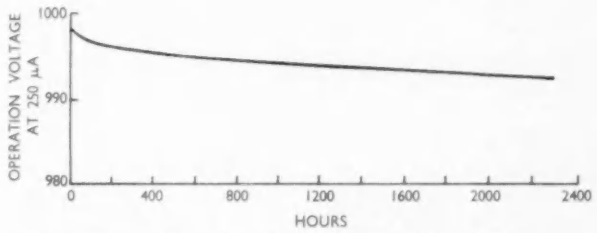


Fig. 4.—Variation of voltage during the life of a 1000 volt SC1 tube.

an application is as follows. A 1000 volt stabilized supply giving 250 μA load current is required, and 1500 volts unstabilized is available. Allowing a tube current of 250 μA, the total current of 500 μA through R_s causes a 500 volt drop, i.e., $R_s = 1$ megohm. The stabilization ratio available, R_s/R, in this case is then, using the appropriate value of R from Table 1, $10^6 \div 3 \times 10^4$ or 33 : 1. The ratio achieved with a particular tube depends on the series resistance, which can be greater if more excess unstabilized voltage is available and must be decreased if the load current is greater.

APPLICATION.

The tubes have been used in a variety of applications where stabilized supplies of high voltage and low current are required. The nucleonic instrumentation field was one of the first to adopt them. Geiger counters usually operate in the range of 400-2000 volts with very low currents and the power supplies for these often use a corona stabilizer. Scintillation counters can also be supplied in a similar manner.

The supply voltage for high-precision cathode-ray tube instruments can also be stabilized by a higher voltage corona tube and they have been used in various specialized applications. One interesting example is in gas chromatography where the components of a gas mixture are separated by diffusion through a column.

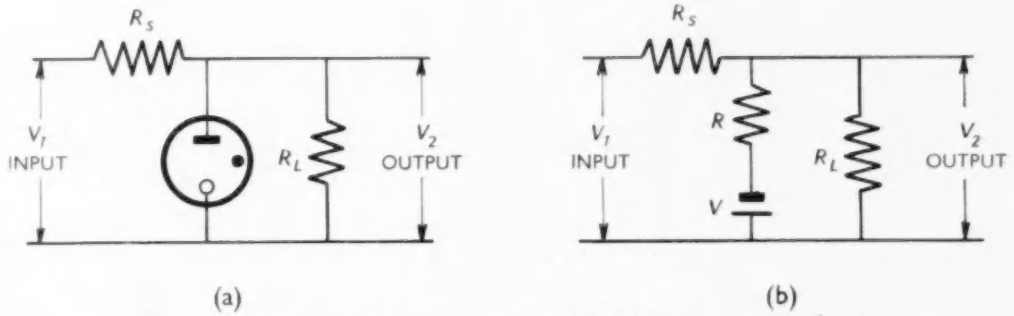


Fig. 5.—(a) Shunt stabilizer circuit. (b) Equivalent circuit.

The arrival of each component at the end of the column is detected by a small change in current through a discharge tube whose supply voltage is stabilized by a corona tube.

The corona stabilizer thus takes its place alongside the older glow discharge tube and extends the range of voltage which can be stabilized by the simple shunt circuit.

Lighting Equipment for the 'Oriana'

Lighting in the public rooms of the new 40 000-ton P. and O. Orient liner 'Oriana' (right) is designed to provide a high level of illumination but to be as inconspicuous as possible. It consists, mainly, of hot-cathode fluorescent tubes concealed in cornices and recessed fittings supplied by the G.E.C.

With an electrical loading of 185 kW spread over some 60 public rooms and entrances, this indirect lighting installation is one of the largest of its kind afloat, and well over 12 000 fittings of about 100 types, all specially designed for the 'Oriana', have been supplied. In addition, the Company has been responsible for the telephone exchanges and equipment, fire alarm system, room switches and pushbuttons.

Cold-cathode lighting concealed in troughs in the Princess Room.

Cold-cathode lighting in the Dining Room.

Hot-cathode lighting installed above louvres in the Monkey Bar.

Structural Design and Development of Graphite Reactor Cores

By R. W. BAILEY, B.Sc., B.E.(Hons.), Ph.D. and
H. A. COX, Atomic Energy Division, Erith.

THE moderator core of each of the nuclear generating stations being built by the British nuclear consortia consists simply of a mass of graphite through which pass channels containing the fuel elements and control-rod assemblies. This structure is supported on a steel grillage within a pressure vessel. The moderator is surrounded by a restraint structure, and the main design considerations are to ensure continuity of fuel channels and to prevent damage to the structure during its operating life.

Although this core structure is essentially very simple, the behaviour of graphite under irradiation is not fully predictable and the design can only be based on the latest available data. A design that can accommodate considerable variation in the physical properties of the moderator is therefore desirable. The following provides a brief description of the development of the reactor cores for the nuclear power stations being built by the G.E.C. and Simon-Carves Atomic Energy Group at Hunterston, for the South of Scotland Electricity Board, and at Tokai-Mura, for the Japan Atomic Power Company.

DEVELOPMENT OF THE TOKAI CORE.

The major problem associated with the design of the Tokai reactor has been the development of a graphite core able to resist the additional loads occurring during an earthquake. The effect of an earthquake on any structure will depend on the nature and damping characteristics of the structure and its foundations, and cannot be predicted exactly. In the same way as in other earthquake-affected countries, the Japanese Building Code specifies that structures shall be designed to withstand a horizontal force at any level equal to the weight of the structure above that level multiplied by a ' seismic coefficient '. The magnitude of this seismic coefficient is given as 0·2, with a provision for increasing the factor by 0·01 for each 4 m (13 ft) by which the height of the structure exceeds 16 m (52 ft) above ground level.

The purpose of the code is to ensure that buildings will have adequate strength to limit, although not necessarily to prevent, structural damage during a strong earthquake. In the case of the reactor core structure, because of inaccessibility for repair once the reactor has been operated, it is essential that no damage should occur that would prevent the functioning of the reactor after an earthquake. Consequently, in the design of the core structure a seismic coefficient of three times that given by the Japanese Building Code was specified.

This would appear to be a very arbitrary design criterion. However, dynamic studies carried out in Japan, and studies of historical records of the magnitude of earthquakes and resulting damage to buildings that have occurred in this particular locality, have shown that these assumptions do form a reasonable basis of design. In the design of the core structure it is necessary to make provision for the transmission of these horizontal forces throughout the core, while at the same time allowing free movement of the core to accommodate thermal and irradiation effects. The magnitude of the problem will be appreciated when it is realized that the weight of the core structure is approximately 2000 tons, and that the total horizontal force which the core structure must be designed to carry is of the order of 1300 tons.

The original proposal for the Tokai core[1] was based on the design then being used for Hunterston, but with a heavy restraint structure to accommodate the earthquake forces. Both designs were based on information which indicated that the subjection of graphite to irradiation produced dimensional changes in the form of growth. This growth was dependent on the direction of extrusion of the graphite block, being a maximum in the direction perpendicular to the extrusion axis, and the structure was so arranged that the growth in the radial direction was a minimum.

The restraint structure of the Tokai design consisted essentially of a cylindrical network of columns with helical bracing. By using stainless-steel columns and mild-steel bracing it was possible to choose a helix angle such that the radial thermal expansions of the restraint structure and graphite tile layers were identical. A pre-stress was applied to the structure which would then transmit the earthquake loading to the supporting grillage by means of the helical bracing. Irradiation growth of the tile layers could be accommodated by elastic deformation of the structure.

The predicted behaviour of this structure became invalid when further irradiation data indicated shrinkage of the graphite following initial growth. These data showed that the initial pre-stress between bricks would be lost, gaps would open up, and the structure would no longer be adequate to resist an earthquake. In order to maintain stability in the core despite the expected shrinkage of the graphite, a number of alternative proposals were investigated, these

being based on two distinct principles.

One proposal was that of the ' compacted ' core, in which the core is consolidated, as shrinkage takes place, by the application of radial forces at the boundaries. In this way gaps between bricks are eliminated and the earthquake forces can be transmitted to the restraint structure by the induction of compressive forces between bricks. The model illustrated in fig. 1 shows an example of this type of design. Between the restraint structure and the graphite core are placed tightening linkages, uniformly spaced around the circumference and operated from outside the biological shield. During start-up and shut-down of the reactor the linkages are operated automatically to allow for different thermal expansion and contraction rates between graphite and steel. Further adjustment is necessary at intervals throughout the life of the reactor to make allowance for the shrinkage of the graphite. Stability is an important feature in the design of the mechanism and the tightening must be carried out in a preselected sequence.

The second proposal was that finally adopted. In this design, gaps due to Wigner shrinkage and thermal effects are permitted to open up within the core, but contact between bricks is maintained by a radial-key system as shown in the model of fig. 2. This structure is contained within a steel cylinder, and whereas for uniform radial displacements at the boundary (such as occur owing to differential temperature effects) the assembly operates as a mechanism, during horizontal earthquake loading the structure is rigid and loads are transmitted between blocks by induced shear forces in the keys.

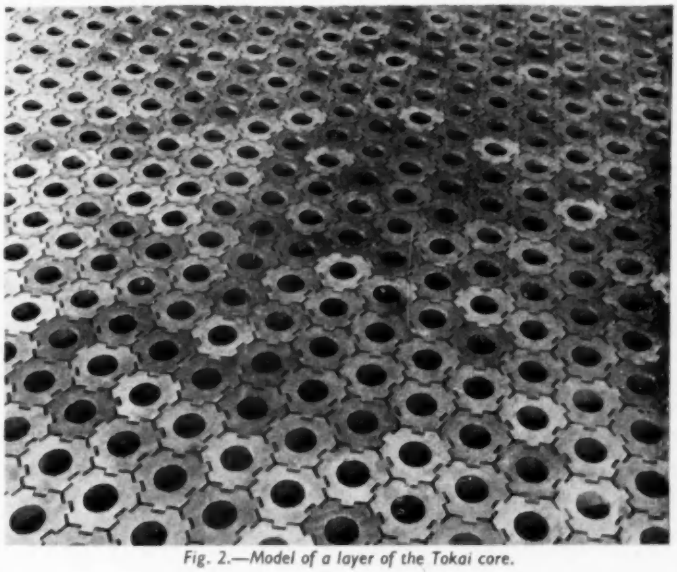


Fig. 2.—Model of a layer of the Tokai core.

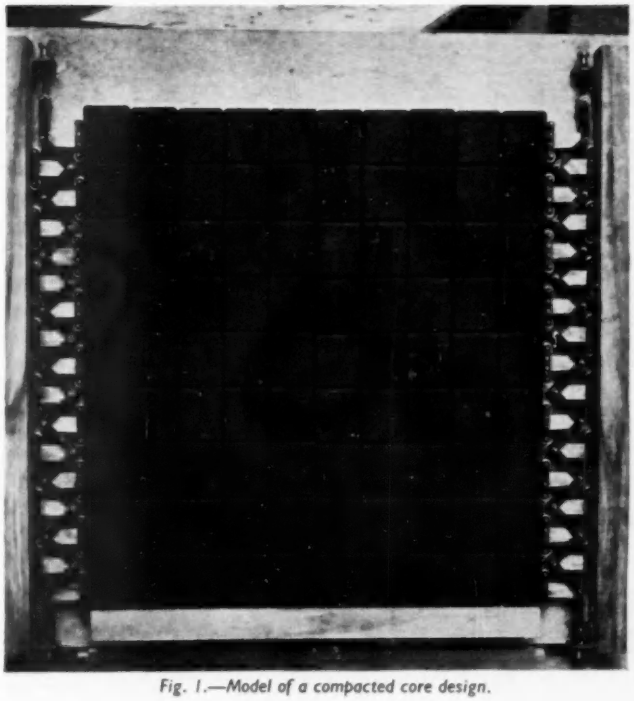


Fig. 1.—Model of a compacted core design.

TOKAI CORE DESIGN.

The Tokai core (shown in sectional elevation in fig. 3) has a nominal overall diameter of 43 ft 1½ in. and a height of 26 ft 9 in., including the reflector which is 2 ft 4 in. thick around the outer edge and 2 ft 6 in. thick above and below. It is constructed of a continuous system of interlocking bricks, each 34 in. long, of hexagonal cross-section. Radial keys and keyways are machined on alternate faces of the hexagon. Each brick is bored centrally, parallel to the extrusion axis, to give on assembly 2233 channels, on a triangular pitch of 9·3 in., of which 181 are control channels and the remainder for fuel. The bricks in any one layer are located in position by means of the key-and-keyway system, while to maintain continuity of channels the bricks across a layer are staggered slightly, thus locating bricks in neighbouring layers. This staggering is arranged so that the thermocouple groove machined in one of the end faces of each core brick is continuous across the core.

The graphite structure rests on 4 in.

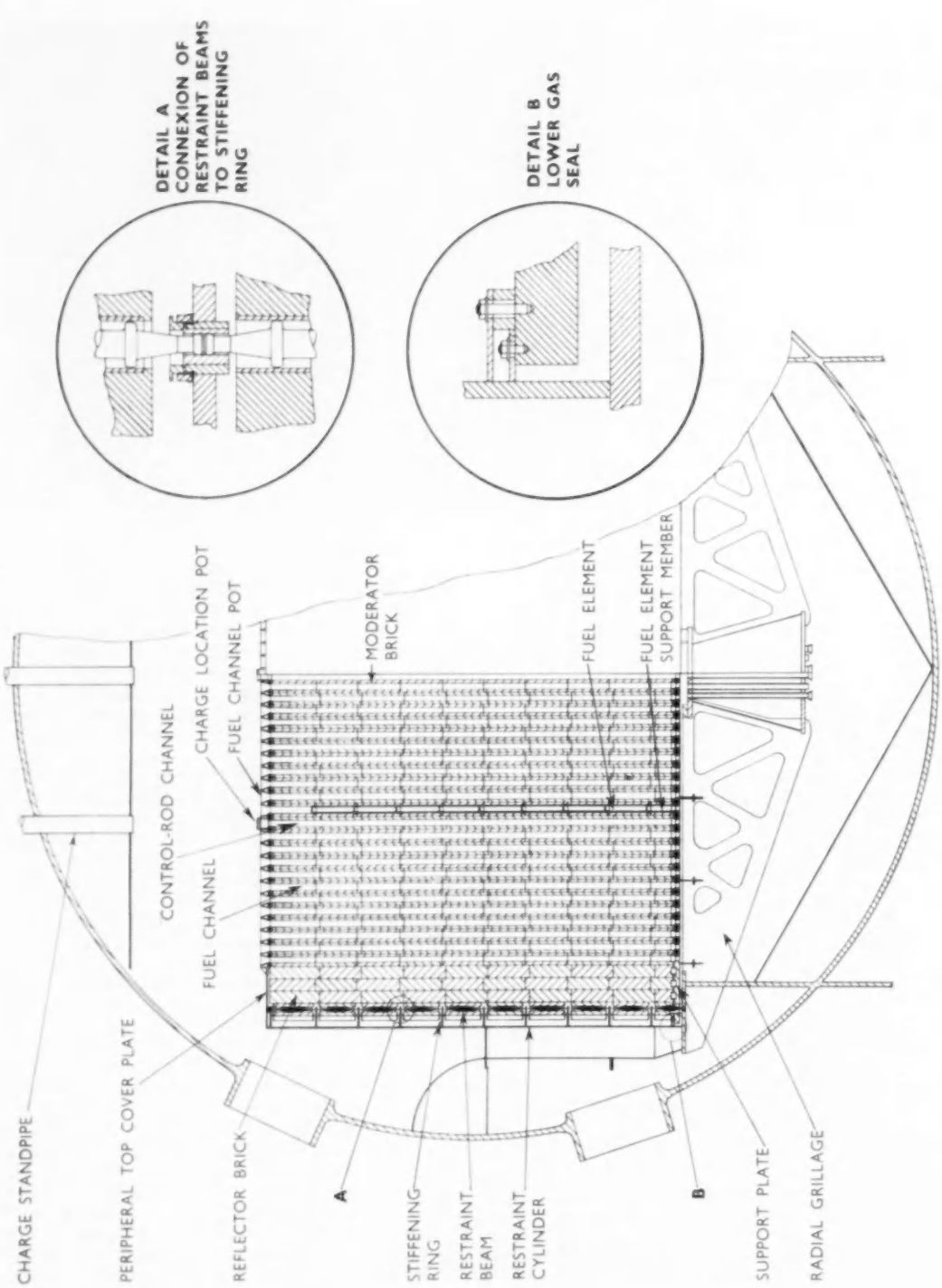


Fig. 3.—Sectioned elevation of the Tokai core.

thick plates which, because of the triangular lattice, are of diamond shape. Each support plate locates 49 bottom-reflector blocks and is supported off the radial grillage by four symmetrically spaced jacking screws. Differential thermal expansion between support plate and grid is provided for by locating one jacking screw, and allowing the remainder to slide radially.

The exact method of locating the bottom reflector to the support plates is under revision. It was originally intended to spigot the bottom reflector to the plates, but if the keys and keyways in these bricks are to take their share of the earthquake force they must have some degree of freedom in the lateral direction in order to take up the machining tolerances between keys and keyways. For this reason the possibility of mounting the bottom reflector bricks on ball races has been investigated. The use of ball races introduces a gas-sealing problem at the bottom of the brick, and the choice of which method to adopt is between simplicity of design with increased loading on the reflector bricks or a more complex design with consequent mechanical uncertainties. A rebate is machined around the periphery of each support plate, allowing mild-steel strips to be fitted between adjacent plates to prevent by-passing of the fuel channels by the coolant gas.

The use of keys and keyways machined along the full length of the moderator bricks affords sufficient strength to withstand the possible earthquake forces. In order to provide sufficient rigidity to withstand these forces, the restraint structure of the core consists of a continuous steel cylinder, welded to the grillage. Considerations affecting the attachment of the peripheral bricks to the restraint structure are:

(*a*) An allowance for the differential vertical thermal expansion between core and restraint cylinder.

(*b*) A flexible connexion such that machining clearances between bricks can be taken up, thus ensuring a more even load distribution on the keys and keyways. A rigid attachment would result in the taking of most of the load by those bricks with minimum clearance.

The attachment (fig. 3) utilizes a tapered beam which is located centrally in each peripheral block by a steel tube co-axial with the beam. Each beam is connected to stiffening rings in the restraint cylinder by means of a double eccentric unit which allows axial alignment and positioning of the peripheral blocks. This tapered beam is sufficiently flexible to prevent the concentration of earthquake forces on any particular brick. Differential thermal expansion in the axial direction between the restraint cylinder and the core is allowed by spacing the peripheral bricks apart on graphite columns, thereby allowing the stiffening ring to move in the space.

The top of the moderator assembly is covered by a layer of charge pots each of which provides a location and seal for the selector tube of the charge machine, a connexion for the piping of the burst-cartridge detection equipment, and a datum which the charge machine can use for radius selection.

Present information shows a large scatter in the Wigner shrinkage of specimens irradiated to the same dosage and temperature, which could produce variation in the height of neighbouring columns of graphite. In order to maintain a gas seal between the channel and charge machine during refuelling, individual charge pots for each channel are used instead of charge pans which cover a group of channels. The charge pots are interlocked by shear keys, in the same manner as the moderator blocks, in order to transmit earthquake loads and horizontal forces imposed during the charging operation out to the restraint cylinder.

Coolant gas is prevented from by-passing the core by means of two gas seals. One is a semi-toroidal seal which is attached to the pressure vessel and grid, and the other a plate seal, constructed from segmental plates welded to the restraint cylinder and bolted to the boundary support plates as shown in fig. 3.

Access for the removal of debris is obtained by omitting the central column of bricks in the core design. It has been shown experimentally that the omission of this single brick in a layer, or column in a group of bricks, has no effect on the stability of the core.

DESIGN OF THE HUNTERSTON CORE.

The original Hunterston core design[2] comprised an assembly of graphite ' bricks ' and ' tiles ', contained

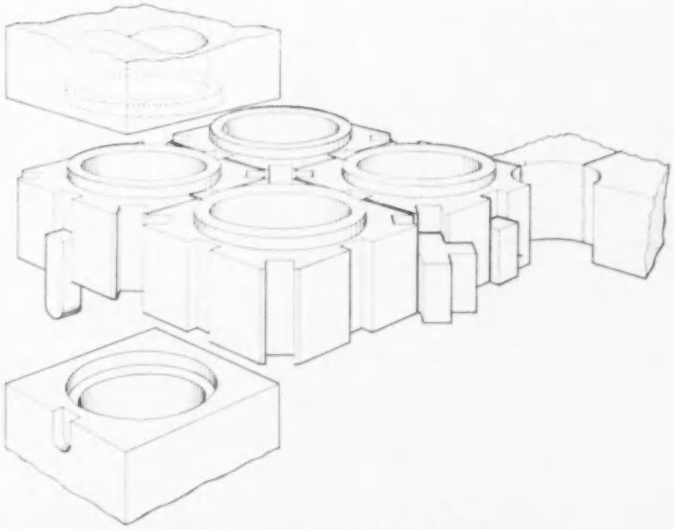


Fig. 4.—The revised brick-and-tile arrangement for Hunterston.

by a steel restraint structure. Compensated garters, having the same coefficient of thermal expansion as graphite, were used to contain the top two layers of the core, and the remainder was stabilized by means of vertical beams pin-jointed at the grid and to a compensated garter at the top.

Under operating conditions this core assembly would take the form of a solid top cap of graphite supported on free-standing columns of graphite. The base of the core was constrained to follow the thermal movements of the grillage, resulting in a maximum gap between graphite columns of 0·017 in.

In addition, there is an essential difference between the Hunterston and Tokai designs, namely that of earthquake consideration. The bricks that form the Tokai core are structural members, whereas the graphite assembly of Hunterston has only light pressure loads to withstand. For this reason it was possible also to retain the brick-and-tile construction for the Hunterston cores.

Fig. 4 shows this brick-and-tile arrangement in which the radial key-and-keyway feature is applied to the tiles only. The tiles are cut with the same grain orientation (extrusion axis) as the bricks, and have

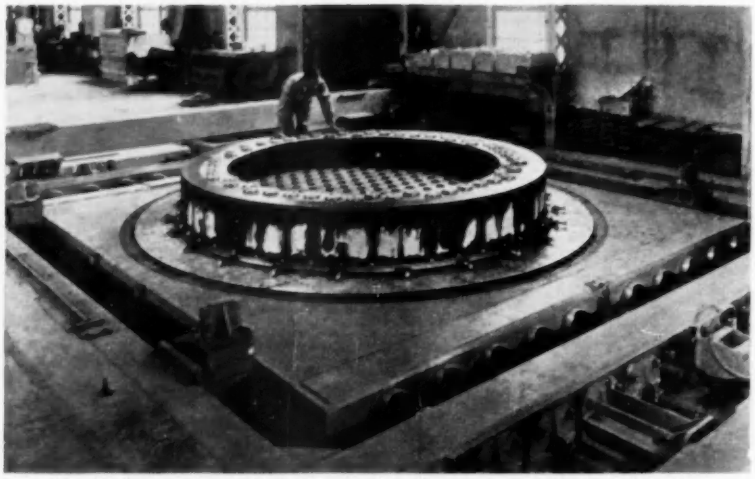


Fig. 5.—Single-layer model for studying boundary reaction under dynamic loading. Photo by courtesy of the Building Research Institute, Japan.

However, extrapolation of the subsequent irradiation data over the life of the reactor showed that gaps between graphite columns of the order of 0·1 in. could occur. The accumulated effect of these gaps would be to enable any one column to deflect through a distance as much as 2·5 in., which was considered unacceptable.

The redesign of the Hunterston core was aided by the experimental work that was being carried out in the design of the earthquake-resistant core for the Tokai reactor. In modifying the principle of radial shear keys, used in the Japanese design, for use in the Hunterston core, three problems had to be considered:

1. The Hunterston design was based on the use of a square lattice while the Tokai core incorporated a triangular lattice.
2. The whole of the reflector graphite had already been machined.
3. The side reflector contained a number of irregularly shaped bricks in which it was difficult to apply the principle of radial keys.

Owing to the lower fast-neutron flux, only negligible Wigner damage is predicted in the side reflector, so that location by radial keys could be confined only to that part of the reflector composed of square bricks.

eight equi-spaced keyways radial to the centre of each tile, with vertical spigots machined on the upper and lower faces to locate the bricks. The core assembly is made up of alternate layers of bricks and tiles, each column being located in position by means of loose keys between neighbouring tiles. Relative rotation between brick and tile is prevented by extending one of the keys into the brick. At particular locations, near control-rod and monitoring-specimen channels, it is necessary to omit some of the cruciform keys, but it has been demonstrated experimentally that this does not affect the stability of the core.

These alterations have not changed the original design conception of the core except in the location of the bricks in space by the radial-key system. Wigner effects merely cause the tiles, and hence the bricks, to grow or shrink towards their own centres. The top two layers of graphite are maintained in position by the compensated garters, which are centralized relative to the pressure vessel by a system of anti-rotation brackets. The remainder of the core is expanded by the thermal movements of the support plates, but movement of the graphite columns is restricted by the interlocking key system.

EXPERIMENTAL INVESTIGATIONS.

Extensive experimental programmes are being carried out in the laboratories of the G.E.C. Atomic Energy Division at Erith, and also at the Building Research Institute of Japan, in order to prove the selected design. Although these studies have been mainly concerned with the Tokai core behaviour under earthquake conditions, the results have also been applied to the Hunterston design, and they provide a better understanding of core behaviour which can be incorporated into future designs.

Strength Tests on Individual Bricks.

Tests have been carried out in order to find a graphite of sufficient strength to provide an adequate safety factor against earthquake loading. These tests have been on blocks of the same cross-section as in the actual core, loaded in a manner to simulate earthquake conditions. Various graphites, both British and Continental, have been investigated and shown to have considerable variation in strength. Variations in the manner of loading as well as minor changes in shape of the brick have been studied.

Distribution of Load Throughout the Core.

Investigations concerned with the distribution of load throughout the core, particularly at the boundary, have been carried out at both the Erith laboratories and at the B.R.I. of Japan.

The model used in Japan is shown in fig. 5, and consisted of an assembly of graphite bricks mounted on a vibration table. The model was attached at the boundary to a mild-steel ring by means of cantilevers, in a manner similar to that used in the actual core. By strain-gauging the cantilevers, the interaction between the core and boundary was studied during the imposed vibrations. Tests were carried out using cantilevers of different stiffness in order to assess the influence on the boundary reaction of the rigidity of the attachment of the core to the restraint structure.

A similar investigation, shown in fig. 6, consisted of a static test on a quarter-scale model of a layer of the core. This model contained the full number of bricks, and was used to study the deformation of the core under horizontal seismic loading as well as to measure the interaction between bricks within the core.

Three-Dimensional Studies.

The investigations mentioned above have been concerned with a single layer of the core. The behaviour of the full assembly is being studied with the aid of a three-dimensional model.

The model consists of six layers of quarter-scale graphite blocks. The restraint cylinder of the actual reactor is replaced by a diagonally braced structure which allows the load transmitted from each layer of the assembly to be measured by strain-gauging the diagonals. A shaking table has been specially constructed for this test so that measurements can be made under conditions of dynamic loading. The model, which weighs nearly 2 tons, can be subjected to a lateral acceleration of the order of $4g$.

The main purpose of the investigation is to enable a study to be made of the axial distribution of load between the core and restraint structure, but studies are also being made of the behaviour of individual bricks under dynamic loading conditions.

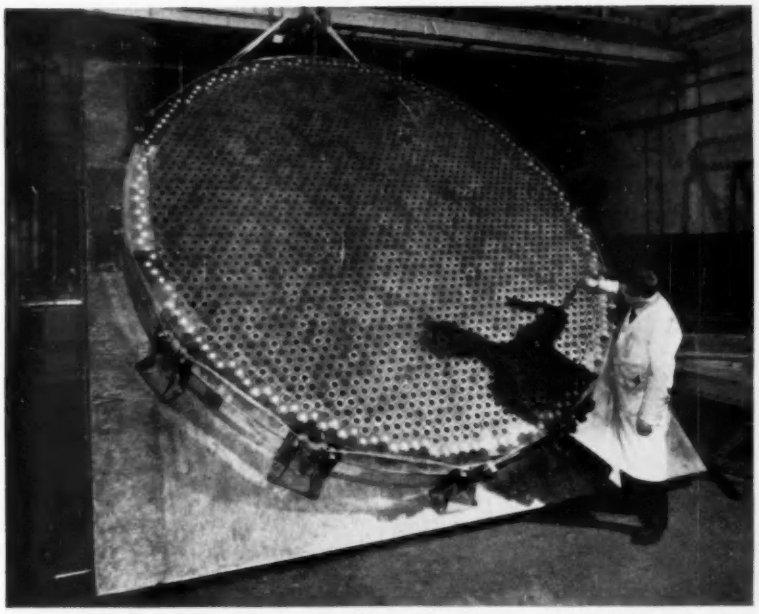


Fig. 6.—A single-layer model of the Tokai core under static loading.

Thermal-Cycling Test.

Under operating conditions the movements of the core blocks are controlled by the steel restraint cylinder. The core structure acts as a mechanism under uniform radial displacements, and to demonstrate this operation the model shown in fig. 7 was constructed. In this model the restraint structure was represented by a conical shell, to which the boundary blocks were attached by means of rollers running in rails fixed to the inside surface of the cone. When moved vertically the cone imposed a radial movement on the boundary bricks. Actuation of the cone in the vertical direction was carried out automatically between set limits by hydraulic

jacks. This simulated thermal cycling was repeated many times without any observable jamming within the block assembly. Similar models have been constructed to demonstrate the thermal-cycling behaviour of the square-lattice construction used for the Hunterston core.

FUTURE DESIGNS.

Owing to the possible occurrence of earthquakes, the Tokai core is a special case. However, the basic principle, that is the fixed location of each brick while still allowing free radial movements to accommodate thermal and Wigner effects, is a desirable feature in view of the still very limited irradiation data on which to base designs. It is thus likely to be incorporated in future reactors. Lateral forces on the core assembly will not normally be large, but may occur, as for example owing to pressure in the event of failure of a gas duct. The large lateral forces arising during earthquakes necessitated the use of keys and keyways along the full length of the bricks in the Tokai core, but otherwise economic advantage may be obtained with brick-and-tile construction in which only the tile layers are interlocked.

To provide a stable core assembly each brick must be located in three or more radial directions. In all strength tests on individual bricks failure has occurred across the brick cylinder and not in the key. There seems little reason for having more than three direction locations, as the increasing number of keys and keyways will tend to weaken the brick structure, but this may depend on the nature of the lattice.

In the Tokai core, a heavy restraint cylinder is necessary to accommodate the high lateral loads. This restraint cylinder determines the radial distortion of the core, so that with a varying temperature distribution up the cylinder some inclination of the bricks from the vertical will occur. This would be undesirable if an unsleeved fuel element were used, as it would increase the chances of gas leakage from the fuel channels. Where lateral loadings are unimportant a restraint structure consisting of vertical columns connecting the grillage to either a steel or temperature-compensated garter at the top of the core may prove preferable.

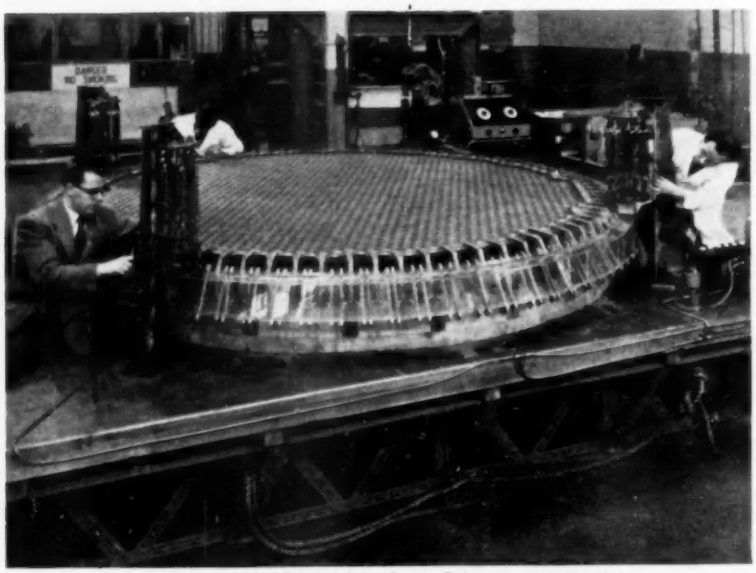


Fig. 7.—A single-layer model of the Tokai core designed to demonstrate the effect of thermal cycling.

The development of core designs for graphite-moderated reactors is dependent on the graphite irradiation tests being carried out principally by the United Kingdom Atomic Energy Authority. These are essentially of a long-term nature and for any particular graphite are subject to extrapolation errors in the early stages. The present core design, however, can accommodate large discrepancies in the growth and shrinkage data and provide confidence in the future operation of these reactors.

ACKNOWLEDGEMENTS.

Thanks are due to the Japan Atomic Power Company and the South of Scotland Electricity Board for permission to publish this paper.

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Development of Guidance Equipment for the Seaslug Missile

By J. M. C. PINKHAM, M.A., Applied Electronics Laboratories, Stanmore.

This article covers the development of guidance equipment for the successful Seaslug Mk. I Missile. A Mk. II Seaslug was announced in the Naval Estimates earlier this year, and The General Electric Company Ltd. will also be responsible for the development of the guidance equipment for this new version.

INTRODUCTION.

SEASLUG is the first anti-aircraft guided missile to be adopted by the Royal Navy. It is being fitted to the 'Hampshire' class of guided weapon ships now being built, which will be used for fleet and convoy protection duties. The Mark 1 version of the missile is now undergoing acceptance trials in the trials ship, H.M.S. 'Girdle Ness' (fig. 1) and the first operational ship, H.M.S. 'Devonshire', is due to be completed this year.

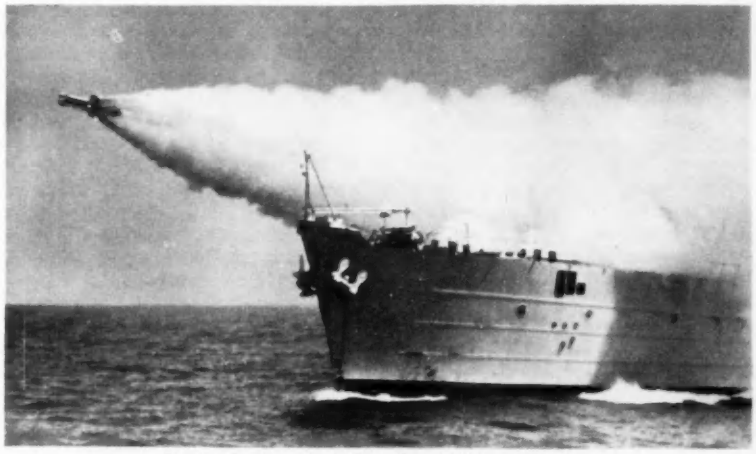

Fig. 1.—Seaslug missile firing from H.M.S. 'Girdle Ness.'

The missile, which is 20 ft long and 16 in. in diameter, with a wingspan of 56 in., is brought by automatic handling gear from the ship's magazine and loaded into a launcher which is slaved in direction to an auto-follow radar. After launch the missile is boosted to supersonic speed by four rocket motors which fall away when they have burnt out: the speed of the missile is subsequently maintained by a further rocket motor which forms part of the main airframe. During the boost phase the missile is uncontrolled, but after the boosts have separated the missile is stabilized in roll and comes under the control of a beam-riding guidance system. A radar on the ship is locked-on to the aircraft target, and signals from the guidance receiver in the missile are used to direct it to fly along the radar beam. The missile then follows the beam until the target is intercepted, when the missile fuze operates and the warhead is detonated.

The G.E.C. has been responsible for the development and manufacture of the guidance equipment in the missile, and the work on this, the first missile project to be undertaken by the Company, was given to the newly-created development establishments at Stanmore and at Brown's Lane, Coventry, which became known as the Applied Electronics Laboratories. (The latter establishment has since been transferred to the new laboratories at Portsmouth opened by the Minister of Aviation on 21 October, 1960.) A subsidiary unit of the Applied Electronics Laboratories has also been set up at the Weapons Research Establish-

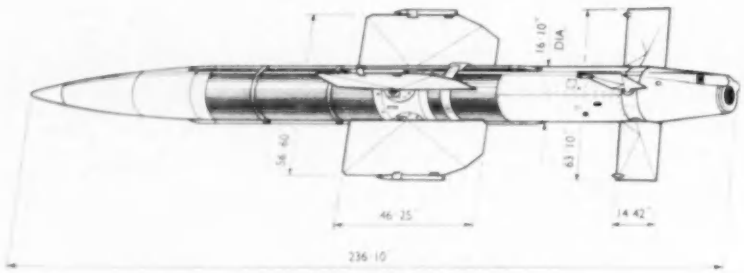

Fig. 2.—Missile outline dimensions.

ment, Salisbury, South Australia, to support the firing trials carried out at the Woomera range. The manufacture of the comparatively large numbers of equipments required for trials, in which a unit once fired is not generally recoverable, was initially undertaken at Coventry, but since 1957 they have also been made at the Company's factory at Broad Oak, Portsmouth.

The other principal contractors concerned with the missile itself are Sir W. G. Armstrong Whitworth Aircraft Ltd. and Sperry Gyroscope Co. Ltd. The work has involved close co-operation with many branches of the Ministry of Aviation (formerly Ministry of Supply), for whom the development was undertaken, and with various Admiralty departments, particularly the Admiralty Surface Weapons Establishment (formerly Admiralty Signal and Radar Establishment), which has been responsible for the design of the Type 901 ship-borne radar.

The work on the project has also included the design and manufacture of automatic test equipment to be used on board ship and in naval supply depots.

EQUIPMENT DESIGN.

The Function of the Equipment.

The Seaslug missile employs cartesian control, that is to say it has two sets of wings and control fins set at right angles (fig. 2), and it is roll-stabilized so that one set controls the up/down (pitch) and the other the left/right (yaw) manœuvre of the missile. The auto-pilot in the missile control equipment, working on signals from accelerometers and a roll-position gyro, ensures the stable flight of the missile, moving the control fins through hydraulic actuators. The function of the guidance equipment is to provide output voltages corresponding to the distance of the missile from the centre of the radar beam in the up/down and left/right directions, and these voltages the control equipment interprets as demands for accelerations, and hence for fin angles, to bring the missile back to the beam centre. The guidance equipment is therefore part of a servo loop containing the radar beam, the guidance equipment itself, the control equipment, the fins, and the aerodynamic properties of the missile: in this servo loop the error signal is provided by the guidance equipment.

The 901 radar on the ship is an auto-follow conical scan radar. In such a radar the aerial radiation pattern is off-set from the axis of the radar, and is rotated about it, the frequency of rotation being known as the spin frequency.[1] Any object which is within the space scanned by the beam, but is not on the axis, will be illuminated with a signal of varying strength as the

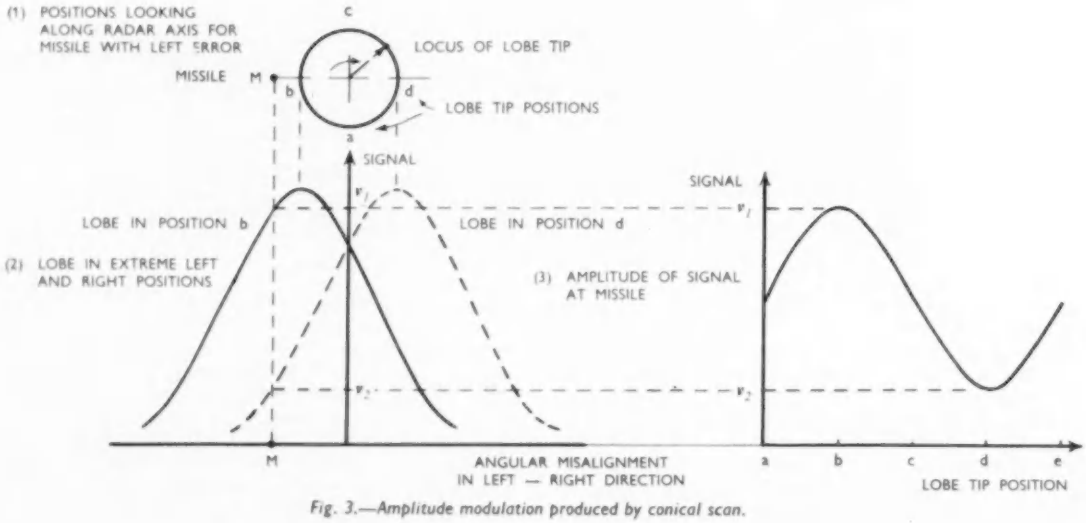

Fig. 3.—Amplitude modulation produced by conical scan.

aerial pattern is rotated, and this is greatest when the radiation lobe is in the direction of the object's misalignment from the axis and least when the lobe is in the position 180° away (fig. 3). If, therefore, a signal from the radar is received in the missile, the amplitude of the spin-frequency modulation on it will indicate the error of the missile from the beam, and a signal derived from this modulation can be used as the error signal for a beam-riding guidance loop. The amplitude of the modulation on the received signal is approximately proportional to the error of the missile from the beam over small angles, but it is proportional to the angular misalignment and not to the linear displacement of the missile from the beam, which is the quantity required in the control of the missile. A multiplying factor proportional to the missile range must therefore be introduced to convert the error from angular to linear terms.

The amplitude modulation of the received signal provides in itself information about the magnitude of the missile misalignment from the axis only, and before the missile can be controlled a further piece of information is required to provide a space reference from which the direction of the misalignment in the up/down-left/right plane can be deduced. This space reference is sent to the missile by modulating the radar transmission with a signal derived from the position of the radar aerial spinner. By comparison in the receiver of the relative phases of the amplitude modulation and this reference modulation, the direction of the missile's misalignment from the beam can also be derived.

Outline Arrangement.

The guidance equipment in the missile consists of two main units, a receiver and an aerial assembly. The polar diagram of the rearward-looking aerial is made wide enough to allow for variations in missile attitude to the line-of-sight from the radar, and the assembly includes a controllable ferrite attenuator which is used as a protective shutter when the missile is immediately in front of the radar just after launch, and subsequently forms part of the receiver a.g.c. loop.

The arrangement of the computing circuits of the receiver is shown in fig. 4. The error-signal demodulator extracts the modulation imposed on the received signal by the radar scan, and this is a sine wave the amplitude of which represents the angular misalignment of the missile from the beam. The multiplying factor proportional to missile range is provided by a potentiometer, known as the range potentiometer, which is part of the time and programme unit in the missile control equipment. The speed of rotation of this potentiometer is chosen to correspond with the range performance of the missile, and the error sine wave is fed through the range potentiometer before being taken to an amplifier. A second demodulator extracts the reference signal sent as a modulation of the radar transmission and this is amplified and filtered to give a reference sine wave.

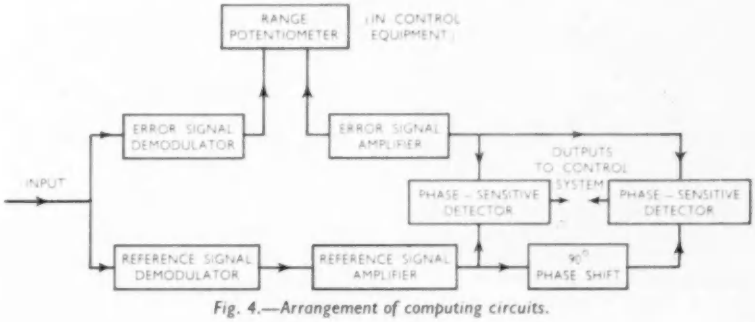

Fig. 4.—Arrangement of computing circuits.

The error sine wave, now representing linear displacement of the missile from the beam centre, is fed into a phase-sensitive detector with the reference signal, and this detector is such that its output represents the amplitude of the component of the error sine wave which is in quadrature with the reference signal. At the same time the reference signal is taken to a 90° phase-shift circuit the output of which is fed, with the error sine wave, to a second phase-sensitive detector. The two detector outputs are voltages representing linear missile displacements from the beam in two orthogonal directions, and constitute the input signals to the missile control equipment.

A high-pressure gas generator in the missile provides the power for the hydraulic system and also drives a 2400 c/s 115 volt, single-phase turbo-alternator. All the h.t. supplies derived in the receiver from this primary supply are stabilized, to give protection against transients or variations of the supply voltage, and to provide the low output impedance necessary to avoid interaction between the various signal circuits in the receiver.

EQUIPMENT DEVELOPMENT.

Early Models.

Firing trials of a guidance system cannot be carried out until the development of airframe, propulsion and control has reached a satisfactory, though not necessarily a final, stage. It was known that it would take

some time to reach this stage on the Seaslug missile itself and preliminary work was therefore done on the design of a beam-riding guidance receiver (designated LR6) for the R.A.E. test vehicle missile RTV1: this was completed in 1951. Although the missile dimensions were not the same as those of Seaslug and the sheet metal construction of the units (fig. 5) was not used in subsequent receivers, this work provided a most valuable introduction to the problems inherent in designing and developing missile equipment.

The first Seaslug missile receiver, designated Type I, is shown in fig. 6. This receiver consisted of three main units, microwave receiver, power unit, and circuit unit. The microwave receiver and some associated circuits were contained in a cast box occupying the full cross-section of the compartment; the other two units were cylindrical with thin removable covers, and were sealed at each end by inflatable rubber rings. A fourth unit, a thin cylinder lying between the power and circuit units, contained the range potentiometer which for this design, unlike subsequent ones, was included in the guidance equipment.

Equipments of this design were used in early missile firings, but the majority of the research and development trials in which the guidance system was proved in flight were carried out with the Type II receiver, the prototype for the final service equipment.

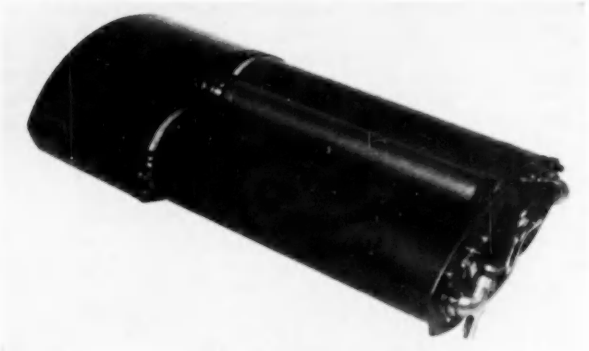

Fig. 6.—Type I receiver.

Type II Receiver.

Although its electrical design was in some ways similar to that of its predecessor, the Type II receiver represented a major departure in mechanical design from the Type I, and it was contained in one box, both the box chassis and the lid being light-alloy castings. The microwave receiver and the power pack occupied the central well in this chassis, and the valve circuits were arranged down each side (fig. 7). Each circuit sub-unit consisted of a main board on which were mounted the rugged sub-miniature valves used, developed specifically for guided weapons use, and a resin-cast block containing the components (fig. 8). The valves fitted into holes in a main web of the chassis which formed a cooling block, the valves being held secure by corrugated metal cylinders. The miniature valves, used as rectifiers and stabilizers in the power pack because of the lack of valves of suitable capacity in the sub-miniature range, were similarly treated, and fitted into bosses on the inner sides of the main webs of the chassis.

The receiver box was pressurized and sealed by a rubber gasket round the lid. Connectors on the two end faces of the box carried the operational connexions to other parts of the missile and the connexions for telemetry. The floor of the main box, which was to the outside of the missile when the receiver was installed, carried test sockets which could be used initially for testing the receiver itself, and subsequently for testing the receiver in the missile when these sockets were made accessible through a removable panel in the missile skin.

The receiver was carried in the missile in a compartment occupying a 120° sector of the missile body, between the wings and the ring at the rear of the missile which carried the control fins. The outer boundary of the compartment was the missile skin itself, approximately 16 in. in diameter, and the inner boundary a tunnel surrounding the blast tube for the sustainer motor which formed the central section of the missile airframe. The overall dimensions of the receiver box were approximately 27 in. long by 11 in. wide by 5½ in. deep, and it contained more than 100 valves and 500 resistors and capacitors.

Type II receivers were made throughout in batches, generally of ten, and even in the early stages of development modifications were introduced into manufacture only at the beginning of a new batch. As soon as the design was sufficiently well-established, manufacture of the receivers was transferred from the Applied Electronics Laboratories model shop to the factory. Although the receivers were being

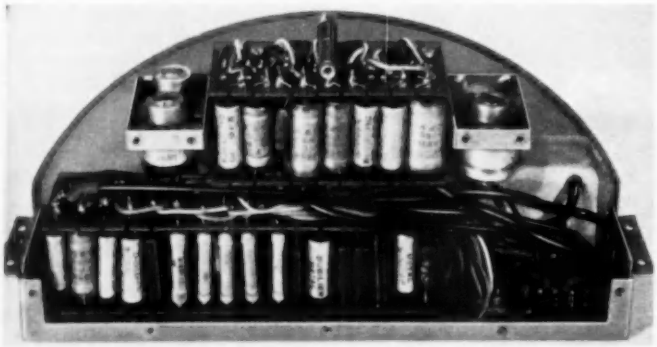

Fig. 5.—LR6 receiver unit.

produced for development firings, they were made to full manufacturing and testing schedules, and this exercise provided most valuable proof that the general design was in fact satisfactory for large-scale production.

Type IV Receiver.

The Type IV guidance receiver is the version for the acceptance trials and operational Seaslug missiles. It is similar in basic principles to the Type II, and bears an obvious resemblance to it, but the mechanical and electrical details differ to some extent.

The main receiver box is of different design from that of the Type II receiver, and the webs carrying the valve holes have been made part of the outer walls of the box. In this way the box has been made easier to manufacture, particularly as the cooling air ducts are now formed by external fins and covering plates and are not integral parts of the casting, and more space has been made available for the circuit sub-units. The microwave receiver has been redesigned and now forms a major sub-unit which can be taken out in one piece. The power pack has been similarly treated, and the sub-units for the four main h.t. supplies are mounted on one removable chassis.

Resilient mountings are used, as with the Type II receiver, to mitigate the effect of the vibration in flight. The rubber mountings employed have a non-linear characteristic, stiffening under heavy loads, so that for small vibration displacements the resonant frequency is kept as low as possible but there is nevertheless no excessive movement with consequent bottoming under high linear accelerations, e.g., during boost.

The electrical design of the receiver is basically the same as that of the earlier versions, although detailed modifications and improvements have been made on the basis of experience with the Type II, some additional facilities have been introduced to meet new requirements of the missile system, and semiconductor rectifiers have been introduced into the power supplies.

The Type IV receiver design incorporates printed wiring in circuit sub-units and in the main interconnecting cableforms between them (fig. 9 and 10). Extreme precautions are taken during assembly to prevent the entry of any pieces of swarf, wire ends, or other conducting particles which might subsequently cause a receiver fault. Fig. 11 shows one of the booths with protecting screens now being used at the factory.

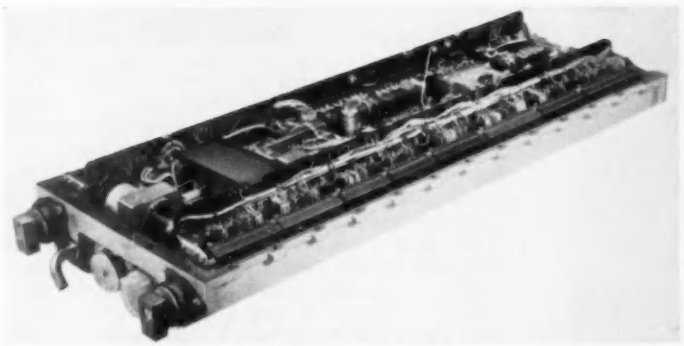

Fig. 7.—Type II receiver.

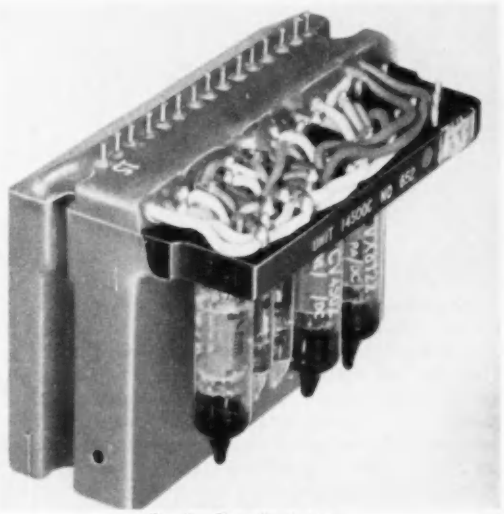

Fig. 8.—Type II sub-unit.

Ground Testing.

Because of the complexity and expense of operating missile equipment in its proper environment, that is in flight, extensive use must be made of substitute ground testing at all stages in the development. In such environmental testing, considerable emphasis is naturally placed on shock and vibration, which are likely to be severe in missile flight. At various times this testing will be directed towards one or more of three main purposes; proving that a design is satisfactory, ensuring that each equipment is correctly made of components of the necessary quality, and investigating faults which may have appeared but not been completely identified in flight trials.

The principal safeguard against equipment failure under vibration is the avoidance of sharp resonances of the main structure or of individual components, and in the design of a receiver a resonance search is first carried out. This is then normally followed by a functional test, in which the receiver on its mountings will be subjected to a range of frequencies extending beyond 1 kc/s, at peak vibration accelerations which may at times be greater than 15*g*. The vibration at the higher frequencies will of course be attenuated

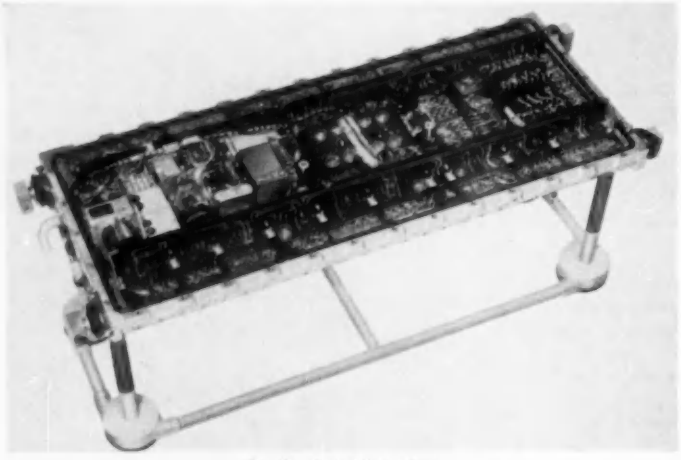

Fig. 9.—Type IV receiver.

by the resilient mountings, but at the lower end of the band the full vibration amplitudes will be transmitted to the receiver itself, and over the resonance of the mounts may be magnified several times. These vibration tests are carried out by mounting the receiver on a jig carried on a moving-coil vibrator. In special tests designed to show up any conducting particles loose in a receiver or inside the valves, a jig has been used in which the receiver can be slowly turned over at the same time as it is being vibrated. Although the flight time for which missile equipment has to operate is short and is measured in minutes, extended vibration tests at high amplitudes must also be carried out to determine the limit of equipment life, and there must be long-duration life tests at the levels experienced in normal transport and ship stowage conditions.

There is a very steep rate of rise of the initial acceleration of the missile by the boost motors, and the performance of receivers under impulsive shock is therefore examined in drop tests. A receiver is mounted in a special cradle carrying a $\frac{3}{4}$ in. diameter steel spike, and this is dropped on to a lead block in which the spike embeds itself. The height of the drop determines, of course, the magnitude of the shock produced. A Type I receiver on a drop test cradle is shown in fig. 12. Tests of receiver performance under sustained acceleration are made on a large centrifuge. All the normal climatic and storage life tests laid down for service equipments are also carried out.

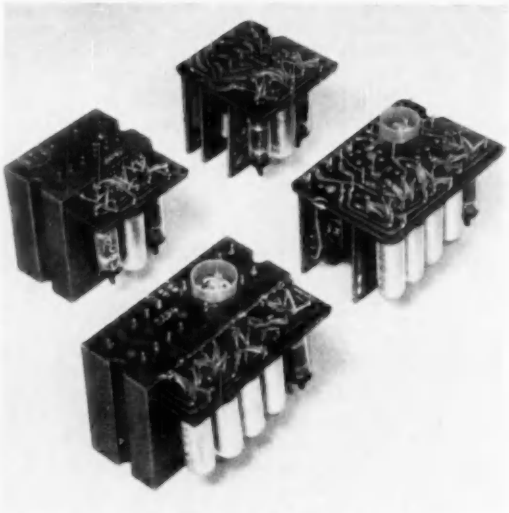

Fig. 10.—Type IV sub-units before and after casting.

Fig. 11.—Booth for clean assembly.

In the checks to ensure the correctness of each equipment, critical components for receiver manufacture are given full electrical tests on receipt, and may in special cases be given mechanical tests as well. Completed receivers are tested under vibration as part of the final assembly and test process, though less stringently than in the design tests, and this operation is primarily intended to be a quick check of the manufacture and inspection that has preceded it, and to reveal any valves which have a high degree of microphony.

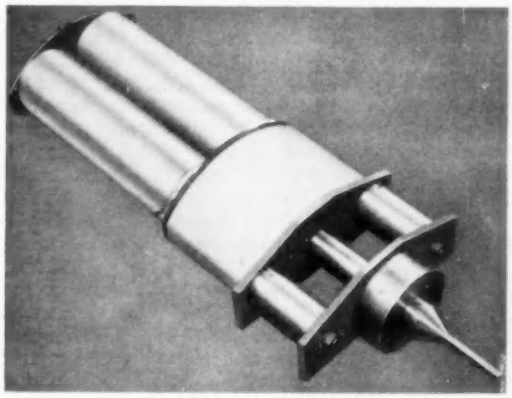

Fig. 12.—Type I receiver on drop test cradle.

SIMULATION.

Apart from its expense and complexity, a missile firing is also unsatisfactory as a scientific experiment because the amount of information which can be recorded on the behaviour of the equipment flown is limited, being generally confined to what can be transmitted on telemetry senders installed in the missile. As much use as possible is therefore made of simulation of flights.

In the simulation work carried out within the Company on Seaslug the main concern has naturally been the operation of the missile receiver circuits on the radar signals received, particularly during the initial gathering of the missile. At the end of the boost period, during which it is unguided, each missile fired will have a certain ballistic dispersion about its line-of-launch, and there will be some additional dispersion due to the effects of wind, errors in launcher position, etc. The first requirement once the guidance system becomes effective is therefore to correct the initial misalignment of the missile resulting from this dispersion, and to bring it to the centre of the radar beam. The missile response to misalignments, of which gathering is a particular case, must be chosen to give a rapid recovery to the beam without involving an excessive penalty from induced drag during the manœuvre, and performance studies on a simulator provide much of the data on which such a choice is made.

The Navy requires a weapon which will be effective against aircraft not only at high but also at low altitudes, where there may be the further complication of signals reaching the missile receiver after reflection from the surface of the sea. Here too the investigation of the beam-riding system must largely be carried out on a simulator because of the need to check performance for widely varying sea states and for all possible dispersion conditions.

When the design of a missile system has been established, simulation still has a most important part to play. A full evaluation of the performance of a missile at all heights and ranges, and for all conditions of target approach, would be prohibitive in both time and cost if it were to be carried out entirely by missile firings. A limited number of firings can be carried out for specified conditions of flight and interception, and these can be shown to be representative of the results obtained for the same conditions on a simulator. The full evaluation of missile performance can then be carried out on the simulator where statistically significant numbers of runs can be made for each set of conditions. In addition it will be possible to simulate missile performance for conditions which cannot be reproduced at all in firing trials, for example because of the limitations in speed and operating height of the available drone targets.

Simulation of Seaslug beam-riding guidance problems has been carried out on large analogue computers designed and built at the Stanmore Laboratories. The Neptune simulator (fig. 13) was built specifically for this work, and was the first to be put into operation. It contains approximately 100 computing amplifiers. The other simulator, Stardac,[2] was built as a general-purpose computer with 200 amplifiers and has been used on a number of projects, to which Seaslug was added when extra capacity was needed for the simulation of low-angle trials (fig. 14).

Each simulator contains function generators representing the radar conical scan, and models of the effects of sea reflections. The output from these units represents the waveform of the signal which would be received by a missile at a given point in space, and is

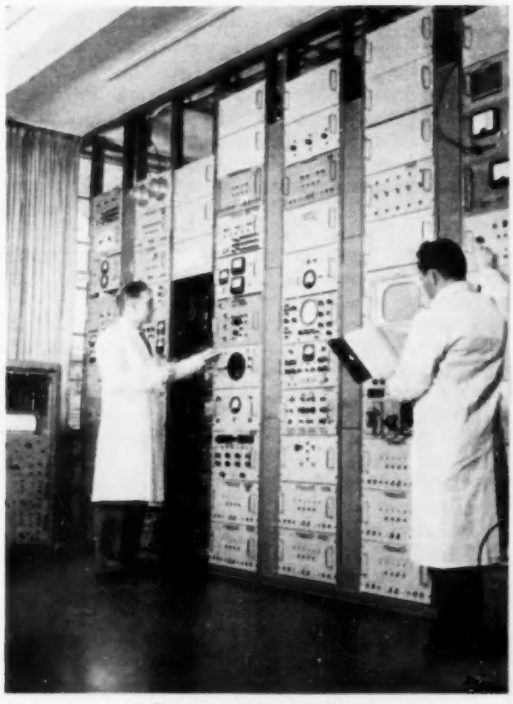

Fig. 13.—Neptune simulator.

used to modulate a signal generator, so that the resulting output is the same as the signal which would exist in the supposed missile receiver. It is possible to include actual missile equipments in the simulation, but because of the special power supplies and cooling air required, and because of the need to have ready access to all circuits so that experimental changes can be easily introduced, the receiver generally used is a special rack-mounted version of the missile equipment, operating from the standard 50 c/s mains supply. The control equipment and the aerodynamic properties of the missile are simulated in an analogue fashion, and the loop is then closed by feeding back to the beam function generator the signals representing missile motion and position. The initial conditions of dispersion, missile characteristics, and beam motion are set in for each run, and the subsequent simulated flight recorded on pen-recorders.

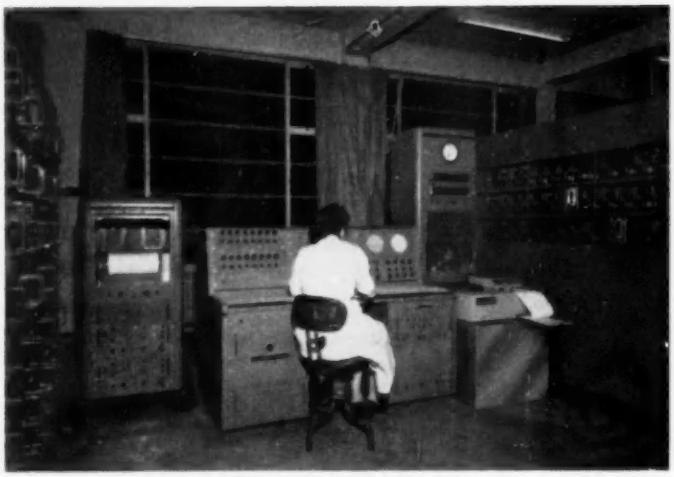

Fig. 14.—Stardac simulator.

A large part of the simulator work consists of the investigation of the effects of proposed changes, and the evaluation of overall performance in the way described; the study of, for example, the statistical distribution of induced drag in missile gathering may involve more than 1000 simulated flights. On other occasions, however, an individual firing will be simulated, either to check the correspondence between the simulator and reality, or to provide evidence for the investigation of apparent peculiarities in the flight performance of a missile. Fig. 15 shows a section of a record from such a simulator run, and the equivalent record from the actual flight with which it was being compared.

FLIGHT TRIALS.

Although the development of guided-missile equipment rests heavily on ground testing and on simulation, there must still be the final confirmation of operation in missile firings. In fact, there are some conditions of flight which it is practically impossible to reproduce on the ground, for example the aerodynamic forces on the control fins of a missile, or the complex environment of sustained acceleration and vibration, and however much thought has gone to making the tests and the simulation as realistic as possible some vital characteristic may have been overlooked until its effect is seen in an actual firing.

When each missile for a trials firing is assembled, the receiver is checked with the other equipment in the round, in particular with the control equipment to which it feeds signals and with the telemetry senders that will transmit back information on what happens during flight. The missile is then sent to the appropriate firing point, the trials ranges at Aberporth on the Welsh coast and at Woomera, or the trials ship H.M.S. 'Girdle Ness'. The missile is again checked before it is put onto the launcher, and some checking may be carried out in the last few minutes before launch to ensure that it is fired in a known and working condition. This round preparation in the factory and at the range is carried out by a combined team of staff from all the contractors concerned. The trials from H.M.S. 'Girdle Ness' gave invaluable early experience to both the designers and the Navy of the particular problems involved in handling missiles on board ship, and it was possible in the later stages of the firings for naval teams to carry out all the preparation themselves. The missiles for the acceptance trials,

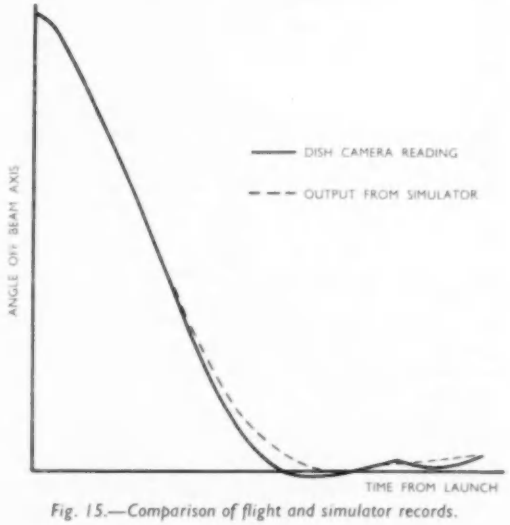

Fig. 15.—Comparison of flight and simulator records.

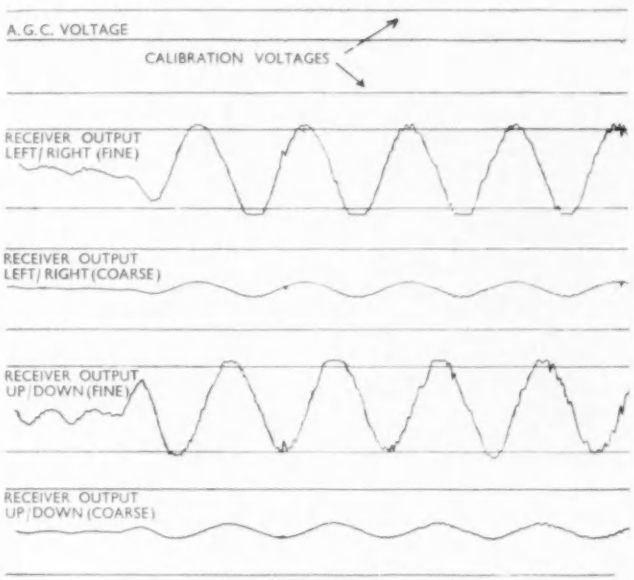

Fig. 16.—Section of flight telemetry record.

once delivered by the contractors are, of course, handled entirely by naval teams.

Information relating to the performance of the guidance equipment in flight is, in the main, obtained from two kinds of instrumentation, dish cameras and telemetry. A dish camera is mounted on the radar aerial director, and set so that the camera axis is accurately aligned with the axis of the radar beam: flares are fitted to the missile to give better visibility on the camera films. The dish camera records carry timing marks, and from measurement of the position of the image of the missile flares in a camera frame the misalignment of the missile from the beam at that time can be calculated. In order to convert the angular misalignment as seen on the camera film into the linear displacement of the missile from the beam, a value for missile range must be derived from one of the sources of trajectory information, generally kinetheodolites or a tracking radar.

This independent measure of missile displacement can then be compared with the telemetry record of the receiver outputs. One or more telemetry senders are installed in each missile to transmit information to special telemetry receivers and recorders on the ground. The guidance receiver quantities normally put on telemetry for such firings include the receiver output, the a.g.c. and the h.t. supply voltages: a section of a typical telemetry record, taken on a multitube recorder, is shown in fig. 16.

The analysis of the trials records for the guidance equipment involves principally the comparison between the actual outputs recorded by telemetry and the outputs expected from the missile position measured on the dish camera record. In successful beam-riding trials the displacements of the missile from the beam are comparatively small, and the analysis is complicated by the noise introduced by jitter of the radar beam, and by the random errors which will be present in both sets of readings. Although examination of the plotted results, as in fig. 17, will

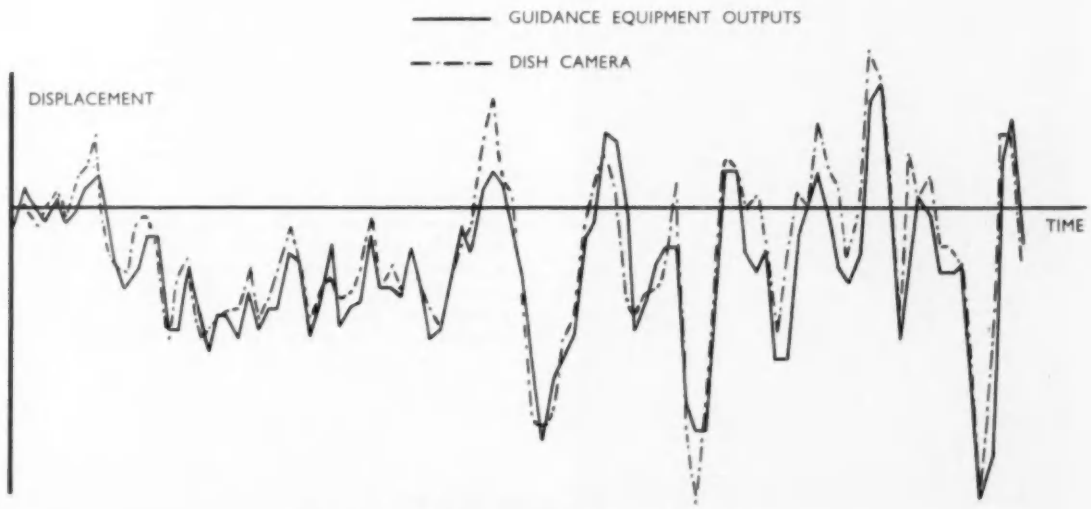

Fig. 17.—Plot of telemetry and dish camera records.

give some indication of the receiver performance, the final assessment must be based on considerable computation, generally including the calculation of the linear regression between the two quantities; in special cases frequency analysis of the outputs may be necessary, involving the use of a digital computer programmed to give auto-correlation functions. If the flight records indicate that a fault occurred in the guidance equipment it may well not be possible to deduce the basic cause of this from the limited information available. In such a case attempts must be made to reproduce the fault in the laboratory, using the telemetry information as a starting point for the investigation.

Many trials of a beam-riding guidance system can be carried out without an aircraft target, as the radar aerial can be programmed to have the appropriate movement, for example for an interception involving gathering at low angle in the presence of sea reflections. Since the provision of a target and its control to the flight conditions required for a particular trial are an additional complication, as much as possible is done in this way. However the performance of the missile must ultimately be confirmed with the radar operating against a real target, and sufficient target interceptions must be carried out to provide the information required for the proving of the missile fuze; there must also be some live-warhead firings. The drone targets used have wing-tip pods carrying cameras to photograph the missile during the interception phase, and for trials in Australia, where recovery of the missile is possible, a small missile-borne single-shot camera developed by the Australian Weapons Research Establishment is also sometimes used. This can be connected to the missile fuze and takes one exposure at the instant the fuze triggers. A photograph of a Meteor target aircraft taken by such a camera is reproduced in fig. 18.

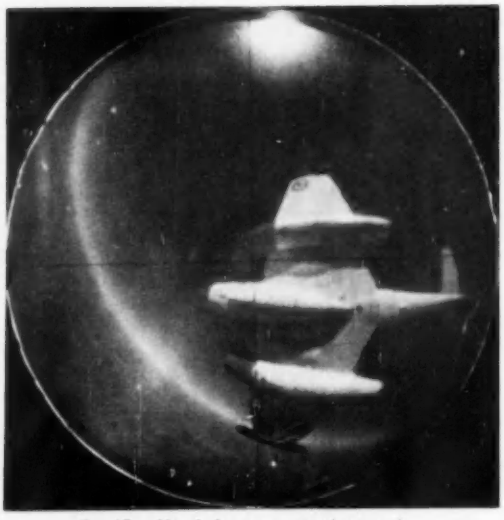

Fig. 18.—Missile-borne camera photograph.

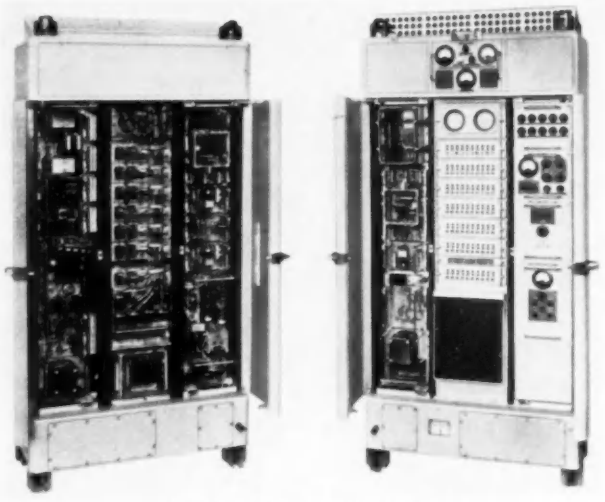

Fig. 19.—G.T.E. guidance console.

RELIABILITY INFORMATION.

A fault data and reliability assessment system has been in operation for the Seaslug guidance receiver from the introduction of the Type II version. Fault reports are made out for every failure, in some cases from sub-unit assembly onwards, including, of course, failures in flight. A fault report is made out as soon as a failure is observed, but since it is essential that the basic cause of the fault should be indentified if possible, the final sections are not filled in until a complete investigation has been made. In addition reports are made out for each major movement of an equipment, when for example it is installed in a missile, or sent out as a spare equipment. The data initially recorded by hand on fault and movement reports is then transferred in numerical codes to standard 80-column Hollerith punched cards.

The information recorded in this way can be analysed using a standard card sorter. Regular summary reports are issued listing the faults recorded in each two-monthly period, and special analyses of predominant faults or of the performance of individual units or component types can be made as required. In addition a regular short-term report is made on manufacturing defects only, and the conclusions from these reports are displayed in the factory.

It is seldom easy, and often impossible, to identify the exact cause of a flight failure. Even if it can be shown that a failure was due, for example, to a short-circuit between the electrode connexions of a valve, it is still generally impossible to say with absolute certainty whether this short-circuit occurred inside the

valve or on the external connexions in the sub-unit. No precise break-down of flight faults can therefore be made similar to that which showed that 40% of the faults recorded in ground testing of the Type II equipment were due to failures of individual components such as valves, resistors, capacitors, etc. It is known, however, that the majority of the flight faults of the Type II equipment were due either to one valve type, (this was confirmed by ground tests), or to the failure of a particular circuit. The valve type has been superseded in the Type IV equipment by a more rugged version, and the circuits concerned modified; the latest information on firings shows that the expected improvement in flight reliability is being achieved.

TEST EQUIPMENT.

The test gear used for receiver preparation during research and development firing trials is operated by trained engineers familiar with the guidance equipment and with the overall missile system. Detailed checks and calibrations of receiver performance are needed to ensure that the maximum value is obtained from each trial firing, and the test gear must be flexible enough in operation to allow for the changes in equipment or in performance specification that will occur in the course of development. It is therefore similar to laboratory test equipment, and must be set up for each test by hand; the information on receiver functions is presented in the normal way on meters and oscilloscopes.

The requirements of the Navy for the testing of missiles in operational use are very different. There the prime purpose is simply to ensure that a weapon is fit to fire within the tolerances laid down on performance: staff highly trained in every detail of the missile equipment cannot be made available, nor can a large amount of time be devoted to the testing of an individual missile on board ship. The test equipment designed and built for naval use has therefore been made automatic in operation, and tests on a Go-No-Go basis.

Test gear of this kind, known as the Girdle Ness Test Equipment (G.T.E.) has been in use throughout the research and development firings from the ship, and the experience gained has been incorporated into the missile test equipments (M.T.E.) that will be fitted in the operational ships and the depots supplying them.

The guidance section of G.T.E. consists of two main units, the control console and the equipment cabinet. The console (fig. 19) allows thes election of any of the guidance equipment tests or overall missile tests. Each test is separately initiated by the operator pressing a button on the control panel: the test is then automatically carried out and the result indicated by the lighting of a pass or a reject lamp adjacent to the press button. For the guidance equipment tests there is also a master pass and master reject lamp indication.

The guidance tests include checks of the power supplies, the receiver tuning, the a.g.c. range, and the beam-riding outputs for various conditions. After a test has been selected, the equipment automatically sets up the appropriate input signal and indicates whether or not the result is within the specified tolerances.

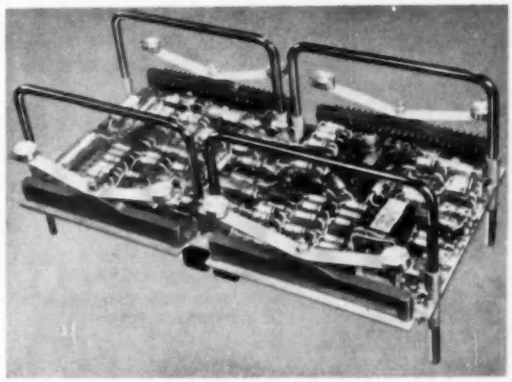

Fig. 20.—G.T.E. sub-unit.

This automatic test equipment is necessarily no less complex than the missile equipment, and in fact contains over 300 valves, and its development has been a major project in itself. Each sub-unit is detachable on a separate panel for ease of servicing, as shown in fig. 20.

THE FUTURE.

At the beginning of the development of Seaslug, little was known about the form of electronic equipment suitable for use in missiles. Designs for new projects can now, however, be based on experience as well as on the latest technical developments.

Future equipments already envisaged will be largely based on the use of transistors, and this together with the introduction of printed wiring and more automatic methods of assembly will increase the reliability, and decrease the weight, the power consumption, and to some extent the complexity of the equipments required. At the same time there is every confidence, both among the manufacturers and the Royal Navy, that the Seaslug missiles which they will be using in the next years will be among the best weapons they have ever had. The number of occasions during the acceptance trials in which rounds without warheads have scored direct hits on high-flying and low-flying targets and destroyed them provides an adequate commentary on the successful development that has gone into the guidance system and into the whole of the Seaslug weapon.

REFERENCES.

1. *Principles of Guided Missile Design.* D. Van Nostrand Co. Inc. Guidance; ARTHUR S. LOCKE. Chapter 16, pp. 580-583.
2. *G.E.C. Journal*, **23**, 4, October 1956. 'Simulators: Some Applications in Industry'. MISS P. L. HODGES.

TECHNICAL LITERATURE

A digest of recent articles and papers by members of the G.E.C. and its associated companies

THE FERROELECTRIC BEHAVIOUR OF SOME NEW NIOBATE COMPOUNDS AND THEIR APPLICATION TO PIEZOELECTRIC DEVICES (795).*

By B. Lewis and L. A. Thomas (Hirst Research Centre).

Solid State Physics in Electronics and Telecommunications. Proceedings of an International Conference held in Brussels, 2-7 *June*, 1958.

The ferroelectric compounds possess the outstanding advantage that the polar axis can be reversed and also switched into any one of several equivalent crystallographic directions by an external field. In ceramics the crystallites are randomly oriented so that their individual piezoelectric effects cancel. Ferroelectric ceramics, however, may be poled by the application of an electric field to produce a resultant sense of polarization and a corresponding piezoelectric effect.

In this paper the authors discuss the properties of niobate ferroelectrics and consider in detail the variants of sodium niobate and of lead metaniobate.

AN ITERATIVE METHOD OF NUMERICAL DIFFERENTIATION.

By D. B. Hunter (Engineering Group, Witton).

The Computer Journal, **3**, 4, *pp.* 270-271, *January* 1961.

The author describes a method, derived from Neville's method for interpolation, of estimating the gradient at any point of a curve specified by a table of values. The process, which is suitable for use on a digital computer, can be applied to either equally-spaced or unequally-spaced tables. An extension for the calculation of higher-order derivatives is also briefly described.

A SIGNIFICANCE TESTER FOR BINOMIAL SAMPLES (835).*

By D. J. G. Farlie (Hirst Research Centre).

The Quality Engineer, **25**, 1, *January-February* 1961.

In the course of quality control work experiments will often be performed to test modifications to the production process for possible improvements in product quality or to compare alternative sources of raw materials. The results of these experiments will often be expressed in the form of attribute data (e.g., numbers 'good' and 'bad') and comparisons made between the percentages of occurrence of some attribute, A, in two samples. This paper describes a slide rule which can be used by the non-statistician to interpret how reliable the evidence of an experiment is in the presence of the variation obtained within the two samples.

COLD PRESSURE-WELDING AND ITS INFLUENCE ON DEVICE DESIGN AND MANUFACTURE (844).*

By D. Boswell and R. Humphrey (Hirst Research Centre).

The Proceedings of the Institution of Electrical Engineers, **106**, *Part B, Supplement No.* 15, 1959.

A brief discussion of the effects of cold welding on container design is followed by considerations of tool design and an assessment of the process on a production scale. Surface preparation and component dimensional control are prime considerations.

VIBRATING REED MAGNETOMETER (884).*

By D. C. Doughty and P. Mossman (Hirst Research Centre).

Journal of Scientific Instruments, **37**, *pp.* 471-474, *December* 1960.

This instrument is a development of the pendulum magnetometer for the measurement of saturation magnetization: it has been found especially useful for exploratory work on new materials, since the test samples it requires are small and of simple shape.

The specimen is attached to the end of a flat non-magnetic spring, maintained in continuous vibration in a non-uniform magnetic field: by observing the resonant frequency with and without the field, the magnetization can be calculated by comparison with a reference sample. Accuracies of about 1% can be obtained on materials with specific magnetizations of 50 e.m.u.

PROPAGATION MEASUREMENTS AT 3480 AND 9640 Mc/s BEYOND THE RADIO HORIZON (898).*

By G. V. Geiger, N. D. La Frenais and W. J. Lucas (Hirst Research Centre).

The Proceedings of the Institution of Electrical Engineers, **107**, *Part B, No.* 36, *November* 1960.

The paper gives an account of scatter-propagation measurements made at S- and X-band during the period May 1957 to May 1959.

The S-band transmitter, using a 3·480 Gc/s c.w. magnetron with a power output of 500 watts, was established at Start Point in Devon. Receiving terminals were set up at Wembley, Middlesex, and Witnesham, Suffolk, at distances of 173 and 247 statute miles, respectively, from the transmitter. Diurnal and seasonal variations in the median level of the received signal are discussed and a comparison is made of measurements taken simultaneously at Wembley and Witnesham.

The transmission path for the X-band system, which used a pulsed magnetron at a frequency of 9·640 Gc/s, also lies between Start Point and Wembley; the pulse length was 2 microsec and the pulse-repetition frequency 500 c/s, the peak power in the pulses being 180 kW. The X- and S-band links were operated together whenever possible, and a comparison is made of the median level and fading rate of the signals received simultaneously at the two frequencies over the same propagation path.

THE THERMAL CONDUCTIVITY AND THERMOELECTRIC POWER OF BISMUTH TELLURIDE AT LOW TEMPERATURES (904).*

By P. A. Walker (Hirst Research Centre).

Proceedings of the Physical Society, **426**, 113, 1960.

Measurements have been made of the thermal conductivity and thermoelectric power of a range of single crystal samples of p- and n-type Bi_2Te_3 between 6 and 200° K. The observed lattice conductivity could be interpreted in terms of scattering by the tellurium isotopes. Measurements on the iodine doped samples showed the existence of appreciable impurity scattering. Interpretation of the thermoelectric power results suggests a multiband structure for Bi_2Te_3.

THE SYSTEM THORIUM-SILICON (912).*

By A. Brown and J. J. Norreys (Hirst Research Centre).

The Journal of the Institute of Metals, **89**, *Part* 7, 1961.

The discovery of a low-temperature form of $ThSi_2$ when Th_3Si_2 is heated in liquid bismuth has led to a detailed examination of the thorium-silicon system by both metallographic and X-ray diffraction techniques. Three new phases, including β-$ThSi_2$, the low-temperature hexagonal form of $ThSi_2$, have been isolated. The other phases, α-Th_6Si_{11}, and β-Th_6Si_{11} are respectively the high-temperature tetragonal and low-temperature hexagonal forms of Th_6Si_{11}. The structural relationships between some of the phases in the system are discussed. A tentative phase diagram is included.

ELECTRICAL PROPERTIES OF LEAD-BARIUM NIOBATES AND ASSOCIATED MATERIALS (918).*

By P. Baxter and N. J. Hellicar (Hirst Research Centre).

Journal of the American Ceramic Society, **43** [11] 578-583 (1960)

The electrical properties of materials in the system lead-barium niobate are described. Particularly useful materials are obtained when between 25 and 50 mole % of lead niobate is replaced by barium niobate. Materials with a 40 to 45 mole % replacement have permittivities of more than 1500 and radial electromechanical coupling coefficients of more than 0·35, but the Curie temperature is then only about 250° C, the minimum value obtained in the system. Higher temperatures are accompanied by somewhat lower values of permittivity and coupling coefficient.

INFRA-RED FARADAY ROTATION AND FREE CARRIER ABSORPTION IN Bi_2Te_3 (920.)*

By I. G. Austin (Hirst Research Centre).

Proceedings of the Physical Society, **76**, 169, 1960.

The Faraday rotation at wavelengths in the range 8-15 μ has been measured on several *n*- and *p*-type single crystals of Bi_2Te_3 using a magnetic field of 17 k oersteds. The results are interpreted as the sum of rotations arising from free carriers and interband transitions. The latter appear to be sensitive to the impurity content. An attempt has been made to separate the components and use the free carrier rotation to estimate the effective mass parameters. Free carrier absorption measurements in the range 8-20 μ are also reported.

GRAPHITIZATION IN ORIENTED CARBONS (921).*

By E. G. Steward and B. P. Cook (Hirst Research Centre).

Zeitschrift für Kristallographie, **114**, 3/4, 1960.

The present knowledge of the crystal structure of polycrystalline carbons is summarized. Of the various factors affecting graphitizability the role of preferred orientation between crystallites is then discussed. Past experimental studies on anthracites, pyrolytic and evaporated carbons, which are relevant to this are reviewed.

It is shown that current views on the crystal-growth process in oriented carbons are unnecessarily restricted by attaching too great an ultimate and exclusive importance to dimensions usually measured by diffraction. The concept of units larger than those measured by X-ray diffraction is discussed and it is shown that some advance towards a general understanding of the various phenomena may be achieved.

PHYSICAL PROCESSES IN SMALL TITANIUM ION PUMPS (924).*

By R. O. Jenkins and W. G. Trodden (Hirst Research Centre).

Vacuum, **10**, 4, *pp.* 319-328.

Experiments with small ion pumps in which titanium is continuously deposited are described. Two types were investigated, the first being a conventional thermionic ionization gauge with titanium evaporating from a directly heated source in the envelope and the second a Penning type of discharge tube in which titanium was sputtered from the end plates. It was found that appreciable desorption of pumped gases took place in the sputter-ion pump but could be made negligible in the evaporation-ion pump.

THE PERFORMANCE OF SOME CORRELATION COEFFICIENTS FOR A GENERAL BIVARIATE DISTRIBUTION (931).*

By D. J. G. Farlie (Hirst Research Centre).

Biometrika, **47**, *pts* 3 *and* 4, *pp.* 307-323.

Association between two variables has in the past been measured or tested by several coefficients, among them

(*i*) Product moment correlation coefficient.
(*ii*) Spearman's rank correlation coefficient.
(*iii*) Kendall's alternative rank coefficient τ.
(*iv*) Probability of concordance.

The efficiency of each of these coefficients in detecting association between two variables is not in general known, but it is known that none is uniformly better than the others.

It is the purpose of this paper first to propose a general class of bivariate distribution functions; secondly, to study how the various coefficients of association compare in efficiency with each other and with a maximum likelihood estimator of the parameter of association; and finally to use the general results to determine which are the best coefficients to use in a number of special cases.

SHAFT-POSITION DIGITIZER USING SYNCHROS (954).*

By T. Roberts (Hirst Research Centre).

Transactions of the Society of Instrument Technology, **13** 1, 1961.

A rotating shaft-position digitizer is described which uses four standard synchro transmitters geared together in 10 : 1 trains. Each transmitter energizes mixing transformers to give five outputs which, when phase-consciously detected, provide a decimal digital code. Type 3000 relays, operated by the phase-conscious detecting circuits, facilitate other forms of coded output and provision is made for freezing this output while the digitizer is rotating.

NOTES ON THE THEORY OF FOUR-LAYER SEMICONDUCTOR SWITCHES (957).*

By A. K. Jonscher (Hirst Research Centre).

Solid-State Electronics, **2**, 2/3, *pp.* 143-148, 1961.

Starting from the accepted theory of four-layer devices, a discussion is developed of the effects of transverse base resistance on three-terminal operation of *p-n-p-n* switches. The treatment is then extended to transient response to two- and three-terminal on- and off-switching.

SYSTEMS USING TRANSISTORS AND TRANSDUCTORS.

By D. A. Ramsay (Applied Electronics Laboratories, Stanmore).

Electronic Engineering, **32**, 390, *pp.* 476-479, *August* 1960; **32**, 391, *pp.* 540-544, *September* 1960; **32**, 392, *pp.* 640-643, *October*, 1960.

Transistors are limited in voltage and power level and are sensitive to temperature variation. Transductors do not have these particular limitations and for some applications these two devices have complementary properties so that their combination provides advantages over the use of one or the other alone. In particular, a transistor control element can be incorporated with transductors to provide amplifiers which are not limited in output power or voltage. Also, highly efficient power amplifiers can be formed with circuits analogous to those of magnetic amplifiers, but in which the output transductor elements are replaced by switching transistors or by controlled silicon rectifiers; in these circuits transductors can be very suitable as control elements. Especially in conjunction with switching transistors, the useful properties of transductors can be exploited to provide small, robust and highly efficient systems.

QUALITY ASSURED BY C.V. SEMICONDUCTOR-DEVICE SPECIFICATIONS.

By A. Lindell (Hirst Research Centre).

I.E.E. Symposium on Electronic Equipment Reliability.

In recent years 'reliable' or 'rugged' specifications for semiconductor devices have been published and these include clauses for physical, mechanical and life tests in addition to electrical requirements. It is the purpose of the contribution to note the quality assured by these specifications (CV7000 series) and to consider their worth.

SURFACES, SEEING AND DRIVING; SOME RECENT STUDIES.

By J. M. Waldram.

The Journal of the Association of Public Lighting Engineers.

In the first part of this paper the author traces the conception of the mechanism of street lighting and the modifications which must be made in design to match the changing properties of the surfaces found on streets today; the second part records recent experiments and new ideas of the function and mechanism of street lighting as the driver sees it, indicating how far we have come and suggesting where we shall have to go if we are to meet the needs of traffic today.

THE SYNTHESIS OF HIGH-PURITY OSCILLATIONS SUITABLE FOR SINGLE-SIDEBAND RECEIVERS.

By P. S. Carnt and E. Ribchester.

The Journal of the British Institution of Radio Engineers, **21**, 3, *pp.* 237-240, *March*, 1961.

An oscillator is controlled by a phase-locked loop, its output frequency being mixed with a selected part of a 100 kc/s spectrum to form an i.f. in the 900-1000 kc/s region. This i.f. feeds one side of a phase detector, the other side being fed by an interpolating signal. The latter may be derived either by another similar stage operating at a lower frequency, or by any suitable method, the required purity in this signal being only of the order of 40 dB. The a.p.c. loop will lock when the i.f. and the interpolating frequency are the same. In the locked condition an additional filter is switched into the loop by means of a quadrature phase detector, and this filter reduces the amplitude of spurious frequencies and noise in the output. The paper discusses factors affecting the resultant purity.

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